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Ground vibration characterization of a missile system for flutter energy definition

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THESIS

Ground Vibration Characterization of a Missile System for Flutter Energy Definition

by

John Barry Hollyer

June 1990

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Changing world scenarios and mission requirements have generated the need to retrofit an all aspect defensive missile system to Patrol airplanes. To this end the AIM-9 Sidewinder was selected and installed on a P-3 at the Naval Air Test Center for envelope expansion and separation tests. The added mass and pitch inertia of this system on the outer wing station may combine with the outer wing characteristics to cause catastrophic flutter. A ground vibration analysis was set up to experimentally measure and analytically model the modal characteristics of the stand alone weapon assembly. This weapon system modal characterization can be analyzed in conjunction with the original bare wing dynamic model leading to an assessment of the flight envelope and a safe in-flight flutter test. The facility and methodologies established in this investigation can also be used to characterize other candidate missile systems. This will provide timely fleet revelant results and generate expected cost savings of over 200K dollars.

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Ground Vibration Characterization of a Missile System for Flutter Energy Definition

by

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Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1978

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Changing world scenarios and mission requirements have generated the need to retrofit an all aspect defensive missile system to Patrol airplanes. To this end the AIM-9 Sidewinder was selected and installed on a P-3 at the Naval Air Test Center for envelope expansion and separation tests. The added mass and pitch inertia of this system on the outer wing may combine with the outer wing characteristics to cause catastrophic flutter. A ground vibration analysis was set up to experimentally measure and analytically model the modal characteristics of the stand alone weapon assembly. This weapon system modal characterization can be analyzed in conjunction with the original bare wing dynamic model leading to an assessment of the flight envelope and a safe in-flight flutter test. The facility and methodologies established in this investigation can also be used to characterize other candidate missile systems. This will provide timely fleet relevant results and generate expected cost savings of over 200K dollars.

TABLE OF CONTENTS

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I. INTRODUCTION

A. BACKGROUND

The P-3 has enjoyed an almost unopposed freedom to operate and perform its primary mission of Anti-Submarine Warfare (ASW) in the world's oceans for nearly 20 years. The greatest threat to open ocean ASW, as it was called in the 1960's and 70's, was the poor quality of the inertial navigation systems which raised fears of losing an airplane in the middle of the Pacific Ocean that was trying to find it's way back to Hawaii from an ASW patrol. This unopposed freedom resulted in the removal of nearly all of the defensive weapons from the airplane during the various major modifications over the last 25 years, as well as the transfer of most weapons control to the Tactical Co-Ordinator (TACCO) and the development of a "fly level " attitude within the community. This has left the P-3 fleet highly vulnerable to any and all air threats.

With the integration of the Harpoon anti-ship missile into its weapons inventory over the last 8 to 10 years and the inclusion of the Surface Ship Surveillance and Control (SSSC), and Anti-SUrface Warfare (ASUW) missions, the P-3 has increasingly been placed in harm's way. Additionally the advances in Soviet naval technology, including the SU-AWACS, inflight refueling of tactical airplanes, and the advent of the new big deck carriers have contributed directly to

the decreased survivability of the P-3 to an ever growing Soviet threat. In fact, the P-3 is now susceptible to virtually every fighter in the Soviet inventory. Just as the mission and world theater of operations determines the susceptibility of a platform to various threats; the community influences, tactics, and the way we handle our airplane determines the vulnerability. As there is not much that one can do about the mission in general, and the world theater of operations in particular, that leaves the community, the tactics, and the way they handle their airplanes as the best chance of improving the survivability of the P-3 in a hot war environment.

To this end the VP community began an aggressive program designed to teach its pilots and crewmen the skills required to survive an air-to-air engagement. These teachings, called Defensive Air Combat Maneuvering (DACM), have been used successfully against numerous fighters including the Phantom II, Kfir, and the Falcon. In fact the tactics have been so successful that the pilots came to realize, during post flight debriefings, that if they had had an all aspect defensive weapon such as an AIM-9 (Sidewinder) the attacker (fighter) would not have engaged unless directed, and could have been killed on most occasions. This finding lead to the P-3/AIM-9 integration program currently ongoing at the Naval Air Test Center (NATC) in Patuxent River Md.

In this test program NATC was tasked to evaluate the separation characteristics of the missile as installed on outer wing stations 9 and 10, and to define the requirements of a system for use

in the P-3 and for the Patrol mission. The P-3 has two low frequency outer wing vibration modes, the outer wing bending mode at 4.7-8 Hertz and the outer wing torsion mode at 17-22 Hertz. Concerns over the carriage of the missile on the outer wing station (#9) was raised by the engineers at the Lockheed California Company (LCC) and a Ground Vibration Test (GVT) was recommended to determine the natural modes and frequencies of the missile system in pitch, as it was to be installed on the P-3. From this one could determine if further modeling would be required to determine if any constructive or destructive interference exists between the missile and the wing. The lateral sway modes (rotation about the longitudinal axis) and yaw modes (rotation about the vertical axis) have never been observed to couple dangerously with any of the airplane structural modes, therefore testing in sway and yaw are not required. The result of the GVT test would be a stiffness model of the system (if required) which could be incorporated into the LCC flutter programs on a computer model of the P-3 wing to determine if there might be a flutter problem with this missile installation. For this test, aircraft manufacturers estimated a nominal 40-60K dollars. Patuxent River was concurrently looking at a Dual Rail Adapter (DRA) which would allow for the carriage of two missiles on each station, and had subsequently been tasked to integrate the Maverick missile for increased air to surface capabilities. NAVAIR decided that all of these modifications would require a GVT to check for flutter on wing station 9, and the estimates increased beyond the funds available.

The dual rail ideas and any use of the outboard wing station (9) for these missiles was then shelved to conserve costs, and keep the remaining test programs going. Wing station 9 is of critical importance to the program because it allows for carriage of the weapon without the loss of a Harpoon station, therefore the need for this testing has remained a high priority.

The current thrust for missile integration and tests for the P-3 and the proposed P-7 airplane, includes the Sidewinder (AIM-9), Maverick (AGM-65), and the Harm (AGM-88), and again the need for a GVT arises. This level of effort mandates the need for a Navy, in-house capability to perform these tests, saving not only project/tax payer funds by cutting costs for the P-3 retrofit/P-7 development program but also providing badly needed new systems to the fleet in a timely manner.

B. PURPOSE

The purpose of this thesis was to develop a Navy 'in-house' vibration test capability employing forced oscillatory inputs over a frequency range of up to 50 Hz. This facility was then utilized to investigate the mechanical vibration resonant characteristics of an AIM-9 missile system in pitch (primary), and yaw and sway (secondary), as it would be installed on a P-3 airplane. Using the results of this test, determine the modal frequencies and shapes in pitch, and the mathematical modeling requirements for a multiple degree of freedom model.

C. SCOPE

The evaluation included the design and construction of a Ground Vibration Test system (GVT), structurally capable of supporting the various missile systems which are to be evaluated for the P-3 and P-7 airplanes, including SIDEWINDER, HARM and MAVERICK. The stiffness of the GVT support structure was designed such that under load from the oscillatory exciter, it did not contribute dynamic response to the missile system installed, while at frequencies below 50 Hz. The GVT system had to be capable of providing oscillatory inputs to the missile in the vertical and lateral directions.

The test frequencies ranged from zero to 50 Hz, with the primary concern centered around 4.7 and 17.5 Hz, the natural frequencies of the existing P-3 wing in bending and torsion. The missile system was shaken vertically, and horizontally so as to cause excitation of the modes about the lateral axis, vertical axis, and the longitudinal axis.

II. TEST SYSTEM

A. GENERAL

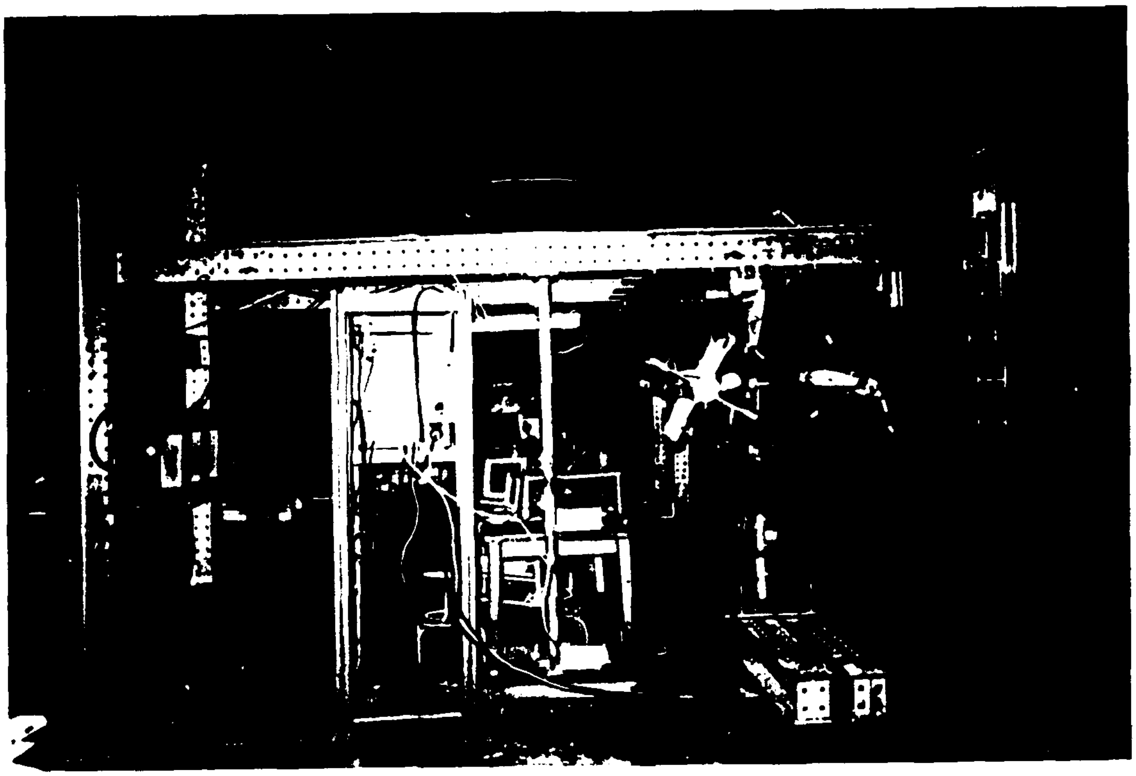
The test system consisted of a GVT base structure; the associated shaker hardware, including a function generator, amplifier, and exciter; accelerometer/force transducer impedance heads with amplifiers and an oscilloscope for data collection; and the missile system, representing the installation of a single AIM-9 on a P-3.

B. GVT BASE STRUCTURE

The GVT base structure was constructed using in-house materials, on the laboratory isolation floor in Halligan Hall at the Naval Postgraduate School (NPS). Stiffening was required to increase the fundamental frequency of the structure from initial fundamental frequencies of approximately 14 Hz, to something above the test frequencies (final fundamental freq was about 53 Hz.). The test structure, as it appeared for testing and data collection, is presented as Figure 1. A more detailed description of the GVT is provided in Appendix C.

C. SHAKER ASSEMBLY HARDWARE

The Shaker Assembly and its associated hardware consisted of a Bruel & Kjaer (B&K) Exciter, Model 4801, with a General Purpose Head, Model 4812; a B&K Amplifier Type 2707; and an EXACT



SIDE VIEW OF THE GROUND VIBRATION TEST STRUCTURE

FIGURE 1

Function Generator Model-340. The amplifier and function generator were mounted in an electronics rack next to the GVT (Appendix A, Figure 2). The Exciter and General Purpose Head (shaker assembly) were mounted to a 20 x 20 x 3/4 inch aluminum plate (Figure 3). For optimum usage flexibility two 8 x 8 inch 'I' beams were mounted on the floor under and parallel to the missile, flanges up, and three 6 x 6 inch 'I' beams were mounted on the strong backs beside and parallel to the missile, flanges out (Appendix A, Figure 4) This allowed the shaker assembly to be positioned around the missile so as to be able to excite it vertically or horizontally from virtually any point along its length. A more detailed description of the individual components is available in Appendix C.

D. DATA COLLECTION

The data collection was done using two quartz acceleration-force transducer impedance heads, with their appropriate charge amplifiers, and an oscilloscope. The impedance heads, both model 288A11, were manufactured by the PCB Corporation of Depews, New York. Calibration of the impedance head (accelerometer) sensitivity settings was accomplished by placing both accelerometers in series, with the appropriate sense setting of the first set into its amplifier. This was labeled accelerometer "A", and was subsequently kept together with it's associated amplifier for all data collection. The second accelerometer output was channelled through another amplifier for the remainder of the testing and was subsequently

labeled as "B". The two accelerometers were then mechanically excited in series and their output wave forms read on the oscilloscope. The wave form of "B" was then adjusted in amplitude through the use of amplifier "B"'s sensitivity until it exactly matched the magnitude of "A". This process was repeated over the entire frequency range of interest and a table of sensitivity setting vs frequency was generated. This calibration table is presented in Appendix B, Table I.

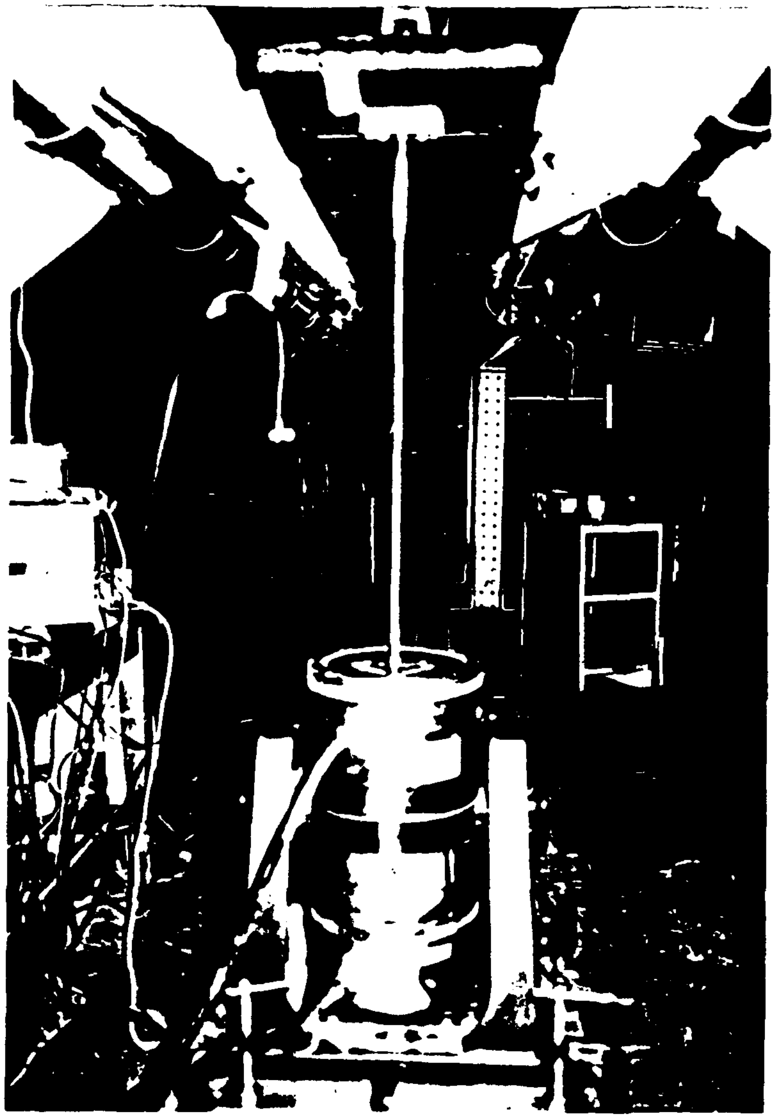
Accelerometer "A" was then mounted rigidly in series with the shaker assembly (see Figure 3) and used to read the exciter wave form and magnitude as well as the force generated at the exciter. The force sensitivity settings were obtained directly from PCB supplied calibrations. Accelerometer B was used as the "roving" accelerometer to read magnitude and phase shift at positions over the entire missile system, defining the accelerations and thus the shape of the components and their interaction. More detailed description of the impedance heads are available in Appendix C.

The data were recorded on hand held data cards for post collection processing.

E. MISSILE SYSTEM

The missile system, as it would be installed on the P-3 airplane, consisted of a P-3 wing station pylon with an integral AERO-65 rack, an ADU-299 adaptor unit, a LAU-7A launcher rail, and an inert AIM-

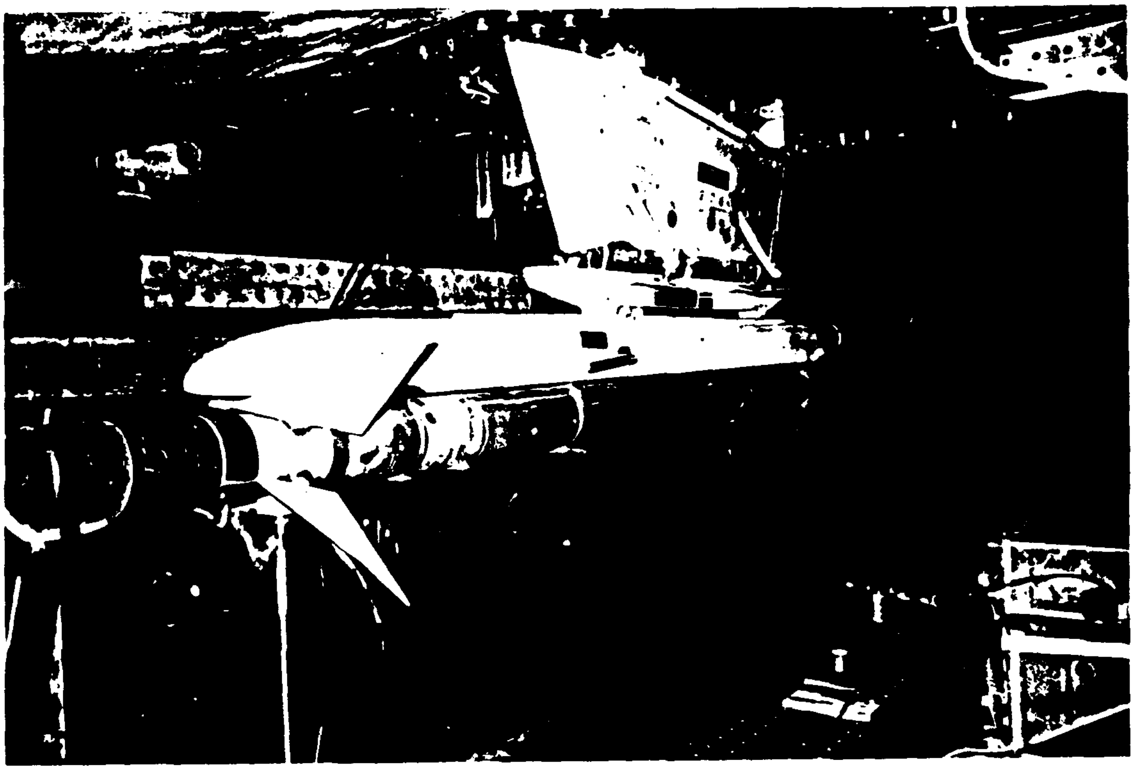
9 series Sidewinder missile. The nitrogen bottle was placed inside the rail empty, for safety reasons. The system was assembled in



GVT SHAKER ASSEMBLY

FIGURE 3

accordance with (IAW) the P-3/AIM-9 Loading Instructions [Ref. 1] generated for the flight test program by the Naval Air Test Center's, Force Warfare Aircraft Test Directorate (FWATD) Ordnance Branch. The up system is shown in Figure 5 below. The missile system was bolted to the GVT structure with spacer blocks, similar in size to those that would have been used to bolt it up to the P-3 wing. A detailed description of the individual missile system components is beyond the scope of this thesis, but can be obtained through the Naval Weapons Center at China Lake Ca. A complete diagrammatic system setup is available in Appendix C, that includes the test article, data collection system, GVT, and the shaker assembly hardware. This missile system installation is considered representative of a production fleet system for the purposes of this test.



SINGLE AIM-9 MISSILE ASSEMBLY

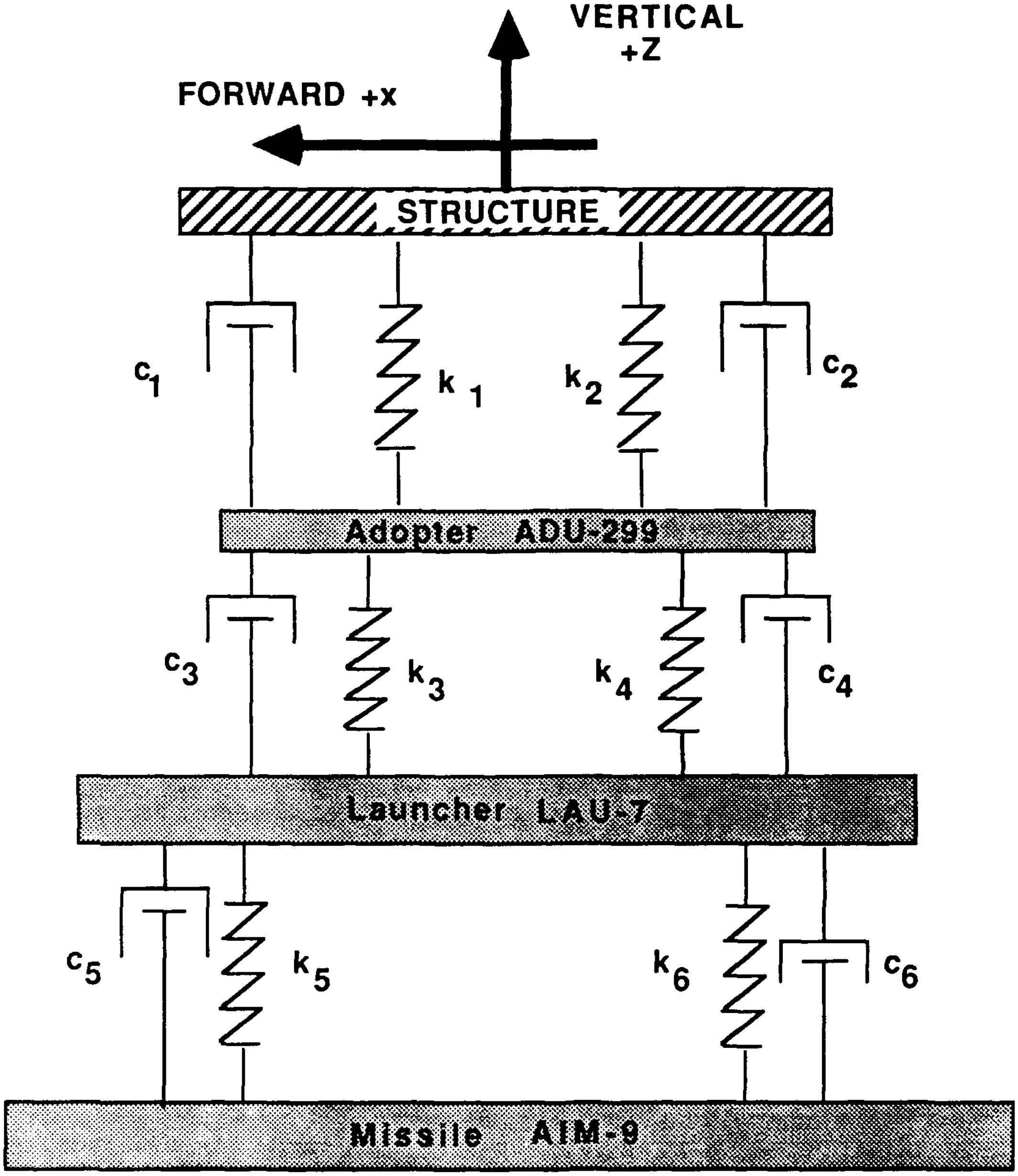
FIGURE 5

III. DATA ACQUISITION AND INTERPRETATION

A. GENERAL

The system was tested for resonance conditions about the three principal axes, lateral, vertical, and longitudinal. The modes associated with these directions will be referred to as pitch, yaw, and sway respectively. Resonance in translation about the vertical axis was also examined. This motion was referred to as heave.

The critical motion that required modeling was pitch and heave, both of which may couple with the resonant modes of the outer wing. Lateral excitation of the system was also performed to evaluate the GVT. In the most general case, each component of the adaptor (ADU), launcher rail (LAU), missile system may move independently such that individual components in the system may need to be modeled separately requiring multiple degrees of freedom to provide an accurate description of the motion. This general case model is shown as Figure 6. In this diagram the components are shown as elastic beams of known continuous mass and inertial properties, each separated by two springs and two dash pots. The pylon and its integral rack were assumed rigid and therefore not included in the model of the missile system, but instead as part of the "wing" support structure.



GENERAL CASE FOR MISSILE SYSTEM MODEL

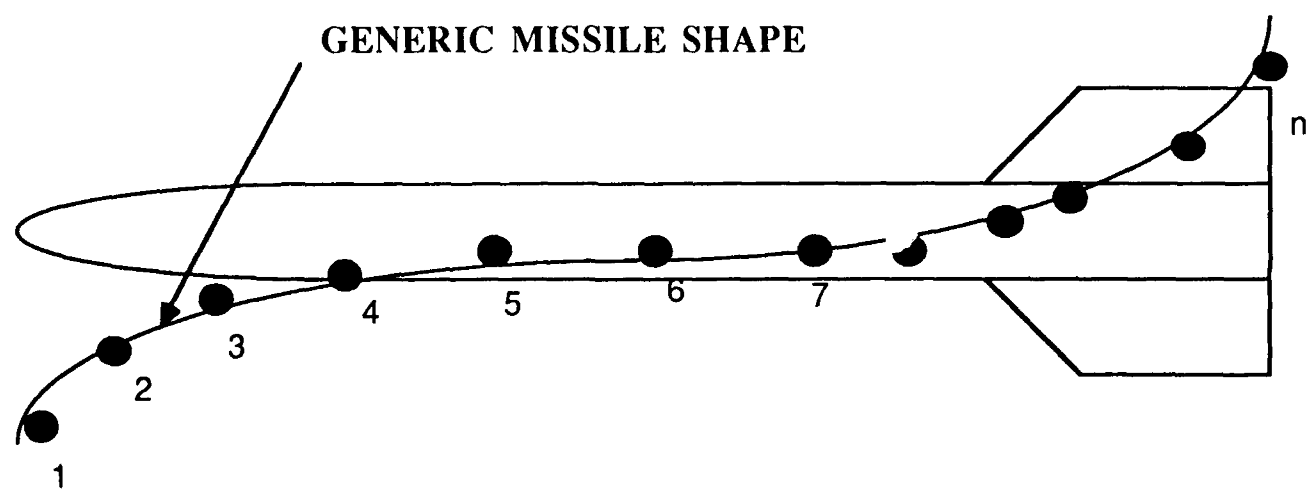
FIGURE 6

If the overall stiffness of each component were known, then the component could be modeled as a series of discrete masses at the location of each known stiffness point. The missile under deflection, with 'n' known stiffness point masses would appear as in Figure 7. In this case a single force $F_j(\omega)$ could then be applied at some location 'j' and the spectrum of vibratory response $X_i(\omega)$ at any coordinate 'i' could be determined.

$$X_i(\omega) = H_{ij}(\omega)F_j(\omega)$$

Where $H_{ij}(\omega)$ is the Frequency Response Function (FRF) between the points 'i' and 'j'. To get a good FRF one must excite the structure sequentially at each point 'j' and take respective readings from every point 'i' at every frequency over the interval of interest. One can quickly see that depending on the number of points over the interval a huge test matrix needed to be implemented.

The missile system has numerous integral components whose individual stiffness and mass properties are not known; therefore, an analytical representation of the overall stiffness over its entire length was not feasible. An alternative would be to experimentally measure and define the FRF. This can be done two ways. The first is to use a spectrum analyzer such as the Scientific Atlanta SD-380 and do an automatic full frequency analysis with up to four channels



MULTIPLE LUMPED MASS MODEL

FIGURE 7

using a full spectrum exciter such as a calibrated hammer or a random exciter. These options were not available at the time, so an alternative method was used to generate the resonant frequencies and associated mode shapes. In this alternate method a sinusoidal forcing input (F_0 Sin $(\omega\tau)$) was applied at several points. The frequency was then varied until resonance occurred. This frequency sweep type investigation was done over the entire frequency range of interest.

The data collected were the normalized point acceleration amplitude referenced to unity, as measured by accelerometer "B", and the input force and relative phase measured by accelerometer "A". The readings, both phase and amplitude, were read from the oscilloscope display. The acceleration data were measured at various points along the length of the missile, LAU-7, ADU-299, pylon and the GVT base structure lower skin plate. The acceleration amplitude reading was in millivolts and was normalized to unity for data reduction and presentation. In as much as the input from the shaker was sinusoidal and the reading was in units of acceleration amplitude, the integration to position, was carried out simply by dividing through by the square of the frequency.

$$z = A \,\mathrm{Sin}(\omega t) \qquad \text{FOR DISPLACEMENTS}$$

$$\ddot{z} = -A\left(\omega^2\right) \mathrm{Sin}(\omega t) \qquad \text{FOR ACCELERATIONS}$$

giving:

$$z = -\frac{\ddot{z}}{\omega^2}$$

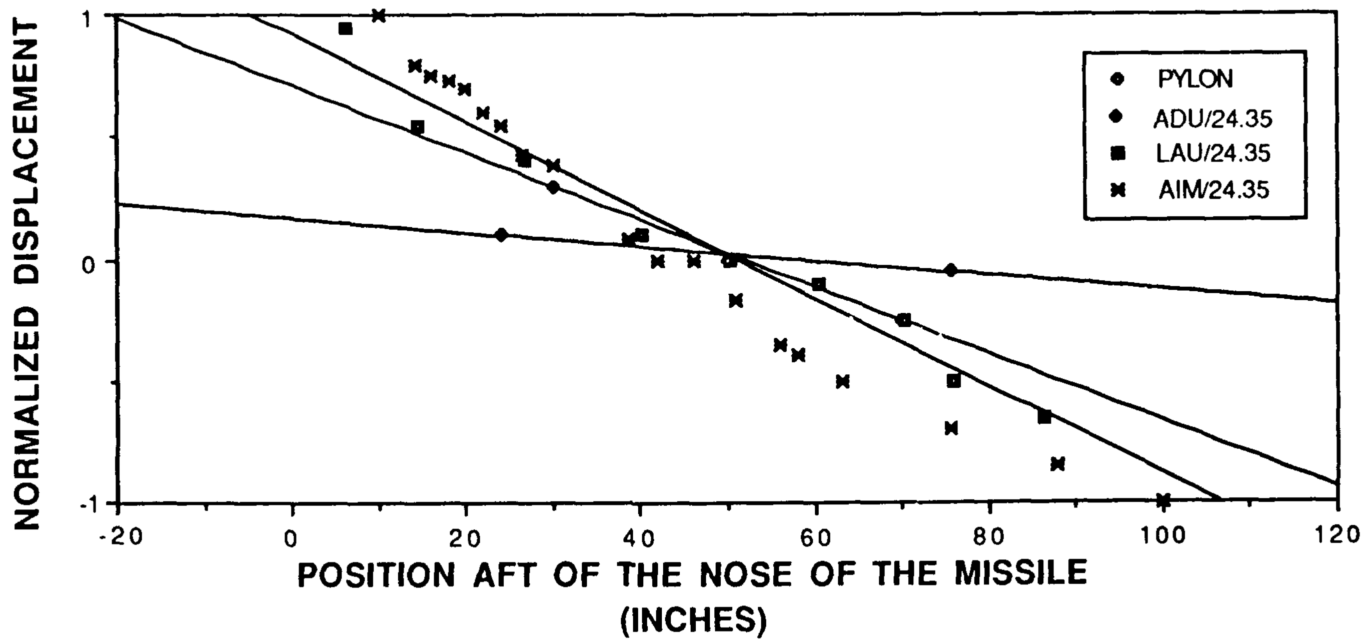
Thus acceleration was directly proportional to the displacement at every point along the length of the components, and normalized point displacement was exactly equal to normalized point acceleration. This shape data reduction can be performed by direct inspection of the acceleration data at contiguous spatial locations. Inspection of the acceleration data will also suggest additional data points as required to improve the shape resolution. The mode's resonant frequency could be determined by abrupt increase in acceleration amplitude with a corresponding decrease in force and further confirmed by a 180 degree phase shift of the frequency response function as seen on the oscilloscope. The resolution of the resonance frequencies is limited and determined by the frequency increments in the digital function generator.

B. PITCH

The missile system was excited in pitch via a sinusoidal vertical input on the missile body near the control canards, at frequencies ranging from 2 to 52 Hz. The excitation force generated by the shaker assembly was varied from 10 to 40 lbs. peak to peak during the test. The first fundamental mode was very apparent and

occurred over a band from 24.4 Hz (T=.041 sec.) to 25.6 Hz (T=.039 sec.) under a force of 11 lbs peak to peak . Within the accuracy of the data collection instruments, the missile, LAU-7, and ADU-299 appeared to move as a single rigid unit over this band with slightly less deflection noted in the ADU (Figure 6). Therefore this first rigid mode, which can be thought of as a "spring" between any two or more components, occurred between the Pylon and the ADU/LAU/missile assembly. At the frequency where the self-amplification of the vibration was observed, the system displacement was in phase with the harmonic forcing function. When the forcing frequency was incremented, within approximately 1 Hz a 180 degree phase shift was observed. The occurrence of this phase shift over such a small frequency range suggested the system was very lightly damped and therefore the damping dashpots may be eliminated in the analytical modeling. The normalized displacement data for 24.4 Hz are plotted in Figure 8, and the tabulated data are presented in Appendix B, Table II. The normalized displacement data for 25.6 Hz. are plotted in Appendix A, Figure 9, and the tabulated data are presented in Appendix B, Table III.

In addition to this primary mode between the ADU/LAU/AIM and the pylon, there was another pitch mode near 34 Hz which appeared to be another rigid mode, possibly between the ADU and the LAU/missile assembly, and a heave mode near 38 Hertz. In this mode the entire missile system translated up and down the vertical



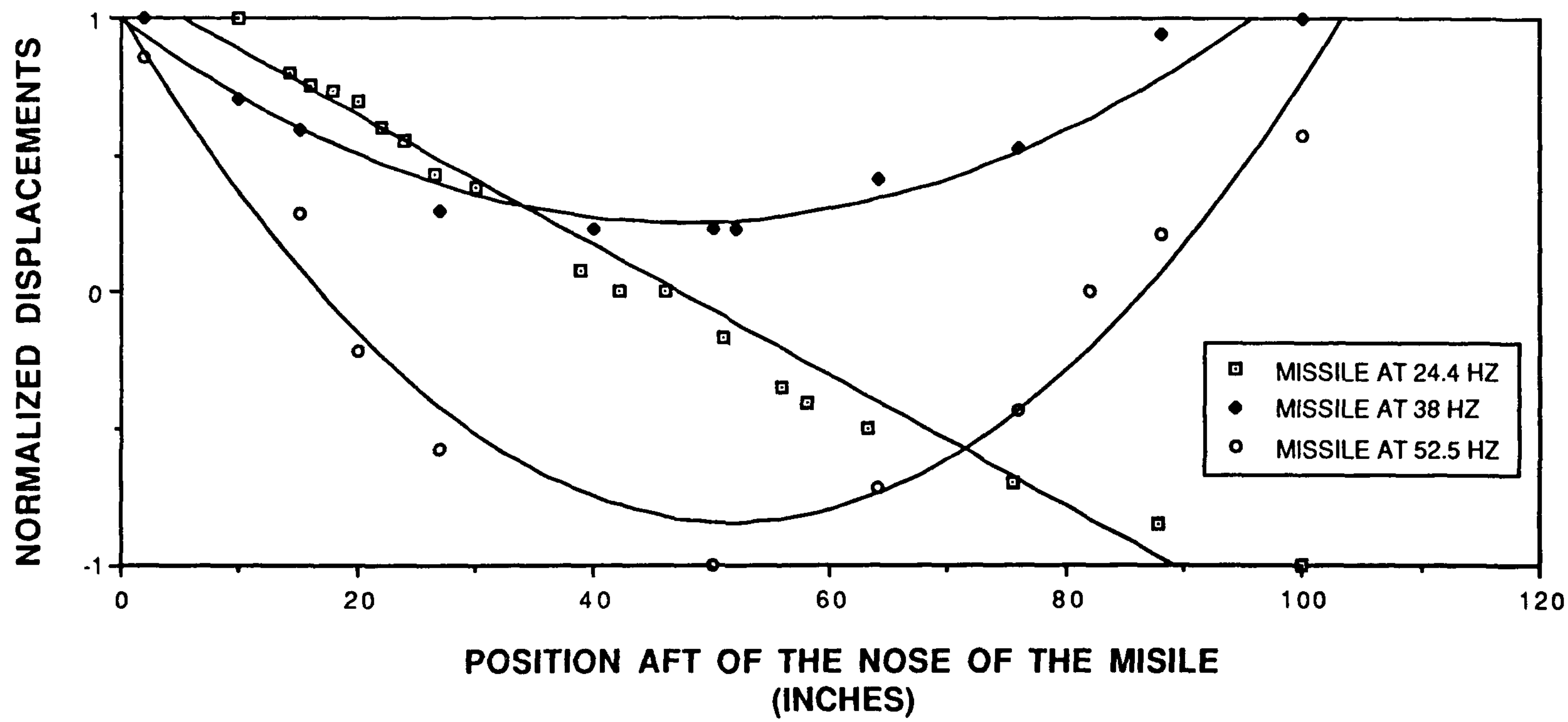
COMPONENT'S POINT DISPLACEMENT VS POSITION AFT OF THE MISSILE NOSE (24.4 HERTZ)

FIGURE 8

axis. Small non-linearities, like chines, appeared in the shape data of the missile as more and more points were taken. These "chines" became more apparent at higher frequencies and seemed to occur at the joints between each missile part. The most pronounced of these was at the joint between the rocket motor and the warhead at approximately 27 inches aft of the nose of the missile.

At the request of the LCC, an attempt to discover the first elastic mode of the missile led to the placement of the shaker at the node of the first rigid mode. It appeared that the first elastic mode of the missile itself, occurred at about 52.5 Hz. This mode was terribly polluted with the motion of the GVT base structure. Data could only be taken on the missile due to the tremendous amount of noise in the accelerometers when attached to the other components. Additionally this mode was not a pure bending mode and a decomposition of the wave form readings would be required to analyze the various modes at this frequency. This decomposition could be done by the SD-380. These data, for the 34, 38, and 52.5 Hz modes, are presented in Appendix A, Figure 10,11, and 12 and Appendix B, Table IV, V, and VI.

A composite view of all three modes of the missile is presented in Figure 13, from which it can be observed that at the lowest frequency (24.4 Hz) the mode shape is that of rigid body motion, as indicated by the straight line. At higher resonance frequencies (38 and 52.5 Hz), increased elastic deformations were observed as indicated by the concave curvatures.



MISSILE MODES FOR SINGLE RAIL AIM-9
24.4/38/52.8 HERTZ

FIGURE 13

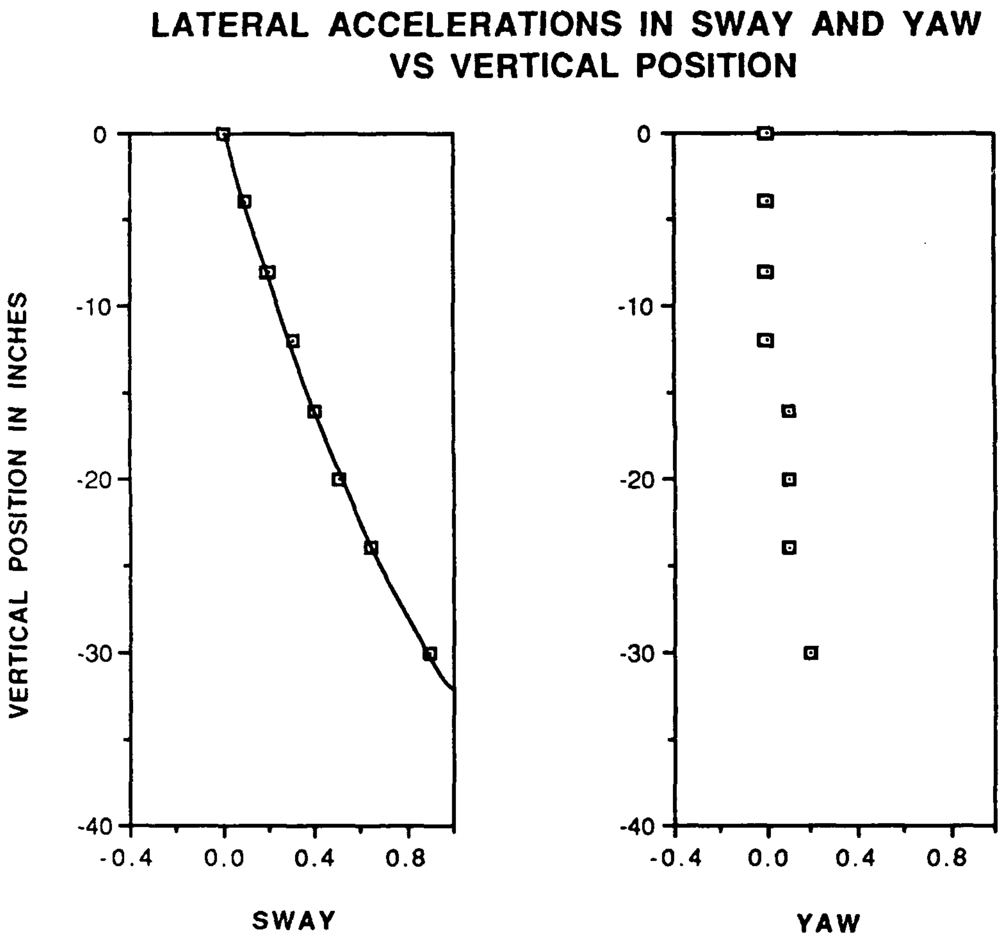
C. SWAY

The system was excited in sway via a sinusoidal horizontal input on the missile near the system Center of Gravity (CG), at frequencies ranging from 2 to 25 Hertz. The excitation force generated by the shaker assembly was approximately 9 lbs. The first mode observed in sway occurred at 7.2 Hz. This mode resulted in significant motion in the skin and infra structure of the GVT. The readings were heavily polluted by the GVT motion and therefore suspect. The structure must be stiffened for lateral excitations before accurate readings can be taken. The trend was however, similar to a bending mode and therefore indicated a lateral flexibility between the components in sway. The data are presented in Appendix B, Table VII, and Figure 14.

D. YAW

The system was excited in yaw, via a sinusoidal horizontal input on the missile body near the control canards, at frequencies from 2 to 15 Hertz. The excitation force generated by the shaker assembly was approximately 10 lbs. The first mode observed was the sway mode, this time at approximately 6.8 Hz. This, qualitatively, appeared to be almost entirely sway, with very little, if any, yaw. The next mode that appeared was at 9.8 Hz. and was mostly yaw. Close examination of the system revealed that there was considerable sway intermixed within the motion, which gave the missile a visual appearance of being elastic. The data are presented

in Appendix A, Figure 15, Appendix B, Table VIII. Figure 15, shows the sway in the system in the yaw mode.



LATERAL POINT DISPLACEMENTS IN SWAY (7.2HZ) AND YAW (9.8HZ) VS POSITION BELOW THE TOP OF THE PYLON

FIGURE 14

IV. MODELING

A. GENERAL

The missile system modeling was formulated to characterize the first modes of the missile system in pitch and heave, over the frequency range of interest (below 50 Hz.). Analytical model formulation requires a general knowledge of the nature of the mode shape, the amount of damping and the number of degrees of freedom. Rational selection of these conditions can be extracted from experimental observations.

The experimentally observed mode shapes were discussed in section III and summarized in Figure 13. It was observed that at the lowest observed resonance frequency (25 Hz), the pitch mode was in fact that of a rigid body. The heave mode observed at a higher resonance frequency (38 Hz) has minor amount of curvature and is not totally rigid. An analytically constraint is that the pitch mode and the heave mode are complimentary pairs therefore the system had to be modeled either as both rigid or as both elastic for both modes. Since the lowest frequency is of greatest relevance to the safe flight test envelope it can be justified to model the system as rigid.

Internal damping of the system is indicated by the rate of phase shift (as a function of frequency) between the harmonic forcing function and the structural response. The rapid phase shift (180 degrees over 1 Hz) noted at the 25 Hertz pitch mode was indicative of a very lightly damped system, therefore the damping can be neglected in the analytical model.

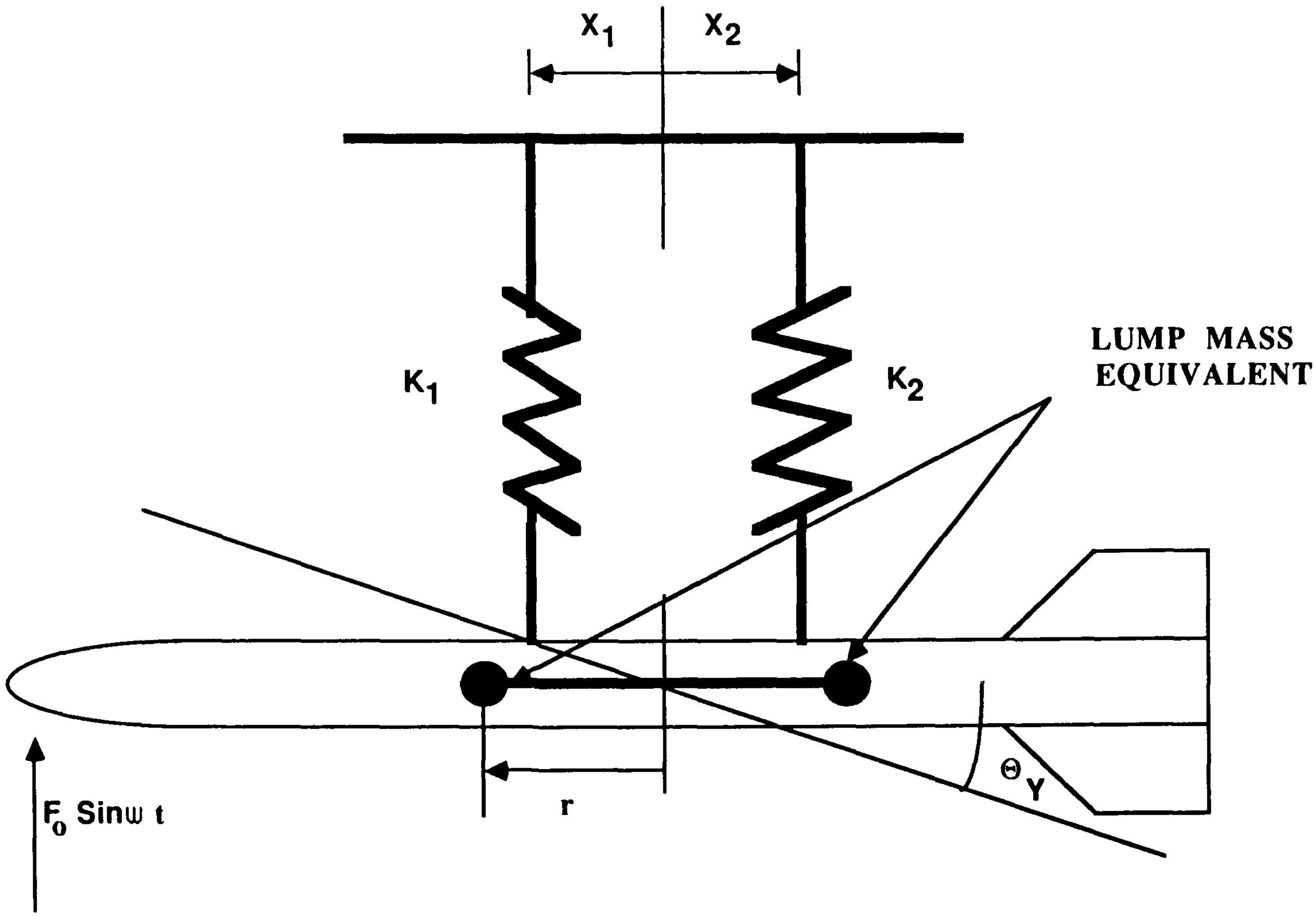
For each single rigid system with no deformations, the number of degree of freedom is reduced to two for the two deformational modes. The congruence of the motion between the components noted in pitch at 25 Hz would seem to allow the AIM, LAU, and ADU to be lumped together as a single mass system, thus allowing for a simple two spring two mass model. This would provide a two degree of freedom model, and correctly model and predict the pitch and heave modes.

Other physical inputs into the model include mass and inertial properties of the missile. They were obtained from actual inertial tests on the missile performed by the NATC, Strike Aircraft Test Directorate, (SATD) Ordnance Branch Gun Tunnel [Ref. 1], and the NWC China Lake general mass/inertia data on the AIM-9 series missile. The LAU, and the ADU data were calculated from various manufacturers specifications, Navy specification data and hand measurements.

As a result of these observation, the Adaptor/Launcher/ Missile system can be analytically represented (in Figure 18) as a two lumped mass system possessing no internal damping, with two springs to provide the two degree of freedom to model the lowest resonance of the pitch and heave modes.

B. THEORY/MODELING

A brief overview of the development of the governing equations of motion for a two degree of freedom model is in order to fully elucidate the mechanics, the physics, the assumptions, and selection processes required to analytically model the system. An exploded pictorial view of the missile system components in pitch is provided as Appendix A, Figure 16. Additionally Appendix A, Figure 17 shows all three types of modes experienced by the missile. The modes of interest for this analysis were the rigid modes of pitch at 25 Hertz and heave at 38 Hertz. The 33 Hertz pitch mode suggested that an additional degree of freedom is amplified probably between the missile/LAU and the ADU. However, the precision required to separate out this mode was beyond the capability of the instruments on hand for the experiment. This pitch mode was therefore not included in the model. The 25 Hz. pitch mode is pictorialized in Figure 18 below. A two mass "dumbbell" shape was chosen based on the assumption that the missile, LAU and ADU were approximately uniform in mass distribution and could reasonable be modeled as beams. The missile, LAU and ADU move together as noted in



MISSILE SYSTEM SPRING MASS MODEL
FIGURE 18

paragraph III B above, and therefore were lumped into one two mass "dumbbell". The dumbbell masses were separated by a distance "r" from the Center of Gravity (CG), r is matched to the radius of gyration of the system to model the rotational inertia. The pylon was modeled as a rigid body and the sway braces (the weak link) become the springs (k_1 and k_2) which support the dumbbell. These hypothetical springs were separated by distances x_1 and x_2. The vertical displacement of the system in heave is denoted as z and the rotation is accounted for by the Theta (θ). The specific motions are:

in heave under rigid body assumption:

$$\theta_1 = \theta_2 = \theta_y$$

$$\ddot{\theta}_y = \dot{\theta}_y = \theta_y = 0$$

in pitch also under rigid body assumption:

$$\theta_1 = \theta_2 = \theta_y$$

$$z(x=0)=0 \qquad \text{at the CG}$$

For a general combined heave and pitch the equation of motion can be developed from the summation of moments equal to the angular acceleration:

$$\Sigma M_y = I_{yy}\ddot{\theta}_y$$

$$\left(mr^2\right)\ddot{\theta}_y + F_1 x_1 - F_2 x_2 = x_3 F_0 \mathrm{Sin}(\omega t)$$

where

x_3 = Location of applied harmonic load with amplitude F_0

$F_2 = k_2[z + x_2 \mathrm{Tan}\ (\theta_y)]$ and $F_1 = k_1[z - x_1 \mathrm{Tan}\ (\theta_y)]$

The small angle theorem allows the substitution:

$\mathrm{Tan}\ (\theta_y) = \theta_1 = \theta_y$ $\qquad\qquad$ $\mathrm{Tan}\ (\theta_y) = \theta_2 = \theta_y$

For the rotational equation of motion this is reduced to:

$$\left(mr^2\right)\ddot{\theta}_y - x_1 k_1\left(z + x_1\theta_y\right) + x_2 k_2\left(z + x_2\theta_y\right) = x_3 F_0 \mathrm{Sin}(\omega t)$$

This leaves a differential equation of motion based on the moment balance in terms of θ and x :

$$\ddot{\theta}_y + \left[\frac{\left(x_1^2 k_1 + x_2^2 k_2\right)}{mr^2}\right]\theta_y + \left[\frac{\left(x_2 k_2 - x_1 k_1\right)}{mr^2}\right] z = \frac{x_3}{mr^2} F_0 \mathrm{Sin}(\omega t) \qquad \text{(Eqn 1)}$$

A similar derivation based on the summation of forces equal to linear acceleration yields:

$$\ddot{z} + \left[\frac{\left(k_1 + k_2\right)}{m}\right] z + \left[\frac{\left(x_2 k_2 - x_1 k_1\right)}{m}\right]\theta_y = \frac{1}{m} F_0 \mathrm{Sin}(\omega t) \qquad \text{(Eqn 2)}$$

These two coupled differential equations describe the motion of a system coupled in pitch and heave. They must be solved simultaneously.

The complementary solutions to these two equations are of the forms:

$$z = z_0 \,\mathrm{Cos}(\omega t)$$

$$\theta_y = \theta_y \,\mathrm{Cos}(\omega t)$$

These will yield the solutions:

$$\left\{\left[\frac{\left(x_1^2 k_1 + x_2^2 k_2\right)}{mr^2}\right] - \omega^2\right\}\theta_0 + \left\{\frac{\left(x_2 k_2 - x_1 k_1\right)}{mr^2}\right\} x_0 = 0$$

and

$$\left\{\left[\frac{\left(x_2 k_2 - x_1 k_1\right)}{m}\right] - \omega^2\right\}\theta_0 + \left\{\frac{\left(k_1 + k_2\right)}{mr^2}\right\} x_0 = 0$$

When theses two equations are simultaneously solved and simplified the resulting equations are fourth order in the angular velocity ω :

$$\omega^4 - \left\{\frac{\left(k_1 + k_2\right)}{m} + \frac{\left(x_1^2 k_1 + x_2^2 k_2\right)}{mr^2}\right\}\omega^2 + \left\{\left[\frac{\left(k_1 + k_2\right)}{m}\right]\left[\frac{\left(x_1^2 k_1 + x_2^2 k_2\right)}{mr^2}\right] - \left[\frac{\left(x_1 k_1 + x_2 k_2\right)}{mr}\right]^2\right\} = 0$$

there are no cross coupled (odd) terms in ω in the absence of damping. A variable change yields two roots giving four coupled frequencies; two positive and two negative. The two negative roots have no physical meanings , leaving the two real roots of the angular velocity ω :

$$\omega^2 = \frac{1}{2}\left\{\frac{(k_1+k_2)}{m} + \frac{(x_1^2k_1+x_2^2k_2)}{m}\right\} \pm \left[\left\{\frac{1}{2}\left[\frac{(k_1+k_2)}{m} - \frac{(x_1^2k_1+x_2^2k_2)}{m}\right]\right\}^2 - \left[\frac{(x_1k_1+x_2k_2)}{mr}\right]^2\right]^{\frac{1}{2}} = 0$$

When the experimentally measured resonance frequencies are expressed in terms of ω , the appropiated spring constants k_1 and k_2 for the model can be obtained from the above two equations. Considerable simplifications is possible when the equations of motion are uncoupled under the condition:

$$x_2k_2 - x_1k_1 = 0$$

This condition simultaneously drives the coefficient of the z term in Eqn 1 to zero and the θ term in Eqn 2 to zero , and the complementary solutions become:

$$\ddot{\theta}_y + \left[\frac{(x_1^2k_1+x_2^2k_2)}{mr^2}\right]\theta_y = 0$$

$$\ddot{x} + \left[\frac{(k_1+k_2)}{m}\right]x = 0$$

When these two equations are solved simultaneously they yield the uncoupled equations of motion for the undamped system as described above.

For motions in heave:

$$\omega_x^2 = \frac{(k_1 + k_2)}{m}$$

For motions in pitch:

$$\omega_\theta^2 = \frac{\left(y_1^2 k_1 + y_2^2 k_2\right)}{m r^2}$$

When combined with the decoupling condition they create three equations and four unknowns. This is not a problem if we can arbitrarily place one of the springs at any given "y" position and solve for the other y and the k's which make that assumption work. That is in fact the case, as can be seen tabulated in Table X below, in-which y_1 was varied over a small range and the associated y_2 and k_1 and k_2 were calculated to support that assumption.

C. MODEL SELECTION

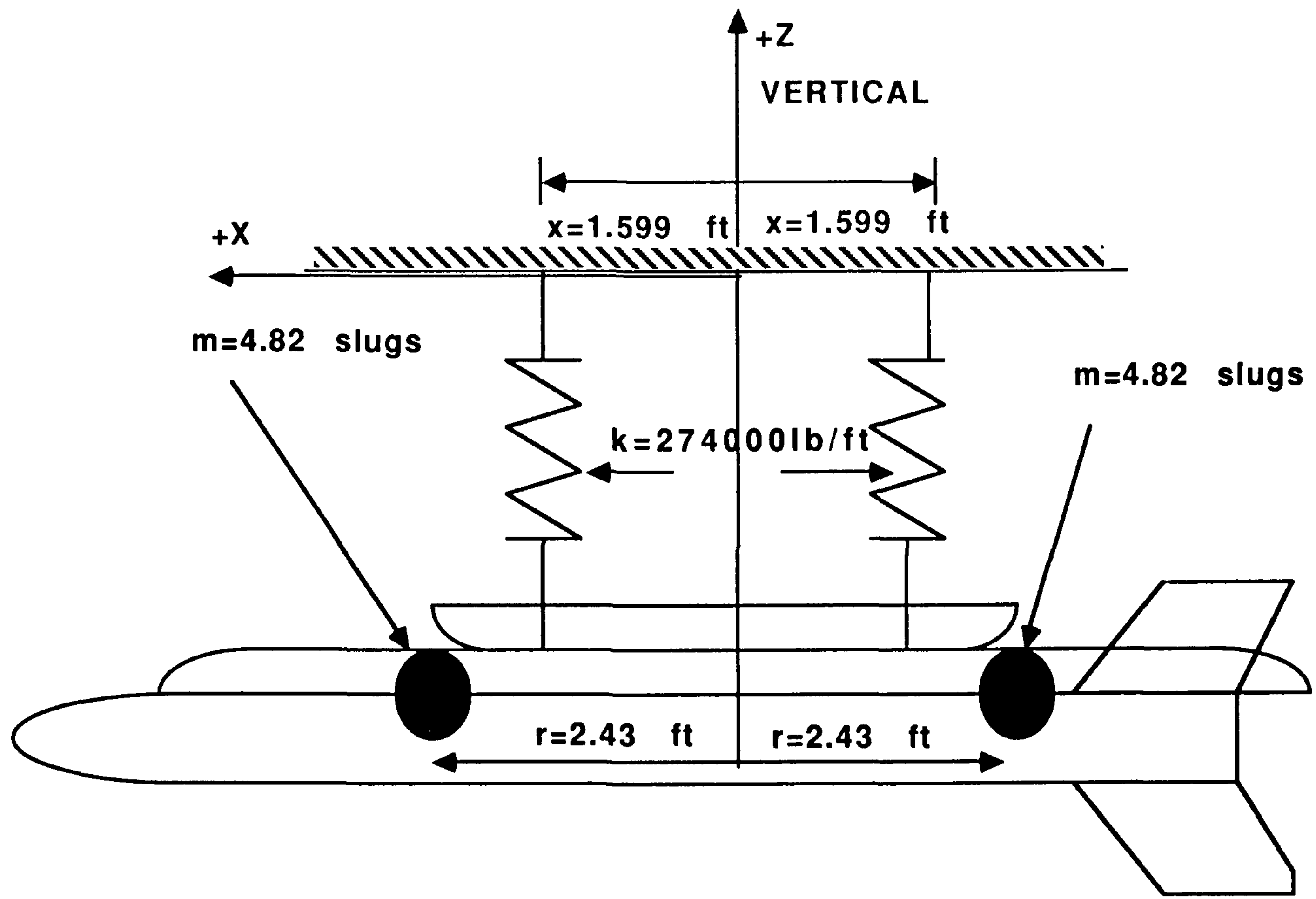
As can be seen in Table X, and graphically in Appendix A, Figure 19, there are several combinations of this model which could accurately portray the motion of this system. The model selected combined the missile, LAU, and ADU together as a two lump mass "dumbbell", having the same mass and inertial properties as they did separately. These lump masses were connected by a

Table X

Variation of Parameters to Verify Position Assumptions

OPTION	ASSUMED Y1 (FT)	CALCULATED k1 (KLB/FT)	CALCULATED Y2 (FT)	CALCULATED k2 (LB/FT)
1	1.599	274	1.599	274
2	0.256	437	1	111.8
3	1	111.8	0.256	437
4	0.127	516	2	33

massless rigid rod of length 4.86 ft. and y_1 was selected equal to y_2 as physically the sway braces and lugs are nearly equal distance from the CG about which the missile pitches. The damping was assumed negligible due to the rapid shift seen in the 25 Hz mode. These assumptions and parameters yield the model depicted in Figure 20 below.



SPRING MASS MODEL

FIGURE 20

V. CONCLUSIONS

A. TEST SYSTEM

Within the scope of these tests, the GVT and shaker system are satisfactory for longitudinal excitation of structural systems, such as missiles, at frequencies up to approximately 50 Hz. Beyond 50 Hertz the fundamental mode of the GVT itself (approximately 53 Hz., T=.019 sec) may cause pollution of data, and additional stiffening of the system may be required.

GVT lateral response is unsatisfactory, due to base support structural deficiencies resulting in low frequency lateral motion under horizontal excitation of test articles. The system was designed for the longitudinal excitation of test articles, and therefore must be modified and stiffened, prior to performing realistic lateral excitation on a pylon/missile model. Alternatives to redesign involve reading, analyzing, and removing the structural motion from the test data, caused by the motion of the GVT.

The accelerometers used, PCB model 288A11, were piezoelectric vice piezoresistive and were unsatisfactory for low frequency (below 5 hertz) response due to low frequency distortion and cutoff.

The EXACT function generator was incapable of fine tuning of frequencies, especially above about 35 Hertz, and was designed for single frequency inputs and not full spectrum inputs.

B. MISSILE SYSTEM

The primary modes and frequencies of concern on the P-3 are the "outer wing bending mode" from 4.7-8 Hertz, and the "outer wing torsion mode" from 17-22 Hertz. The variation goes proportionally with fuel and stores loadings. Within the scope of this test, the first fundamental longitudinal dynamic response frequency (25 Hertz) of the single rail AIM-9 missile system is sufficiently above the outer wing torsion mode of the airplane, even in the worst fuel stores case, that it is compatible on the outboard wing stations (numbers 9 and 18) of the P-3 series airplane for in-flight flutter tests, through out the limits of the basic airframe.

Within the scope of this test the torsional spring-mass model of the missile system described above, satisfactorily models the single rail AIM-9 missile system at the first rigid mode frequencies in pitch and heave.

VI. RECOMMENDATIONS

A. TEST SYSTEM

Modify the test structure to provide stiffening for lateral excitations of the test article. The entire structure could be stiffened by replacing the lower 3/16 inch skin by a much thicker skin, something on the order of 1/2 inches. Other avenues of approach include internal transverse bracing, between the three internal cross stiffener "I" beams (Appendix A, Figure 21), or a complete redesign of the structure.

The two piezoelectric accelerometers used for data collection should be replaced with 5 or 6 piezoresistive accelerometers so as to ensure no low frequency (below 5 Hz.) distortion and allow for the integration of the SD-380 Spectral Analyzer, in the 4-channel mode.

The SD-380 Spectral Analyzer should be integrated in to the data collection system, and linked to the IBM PC/AT with the ENTEK Corporation's EMODAL, modal analysis software package. Both of these items are currently on board the Aero department, and could be integrated into the system to automate the collection, analysis, post processing, and generate multiple degrees of freedom modeling, of the vibration data. These will be needed for the dual rail missile installation tests.

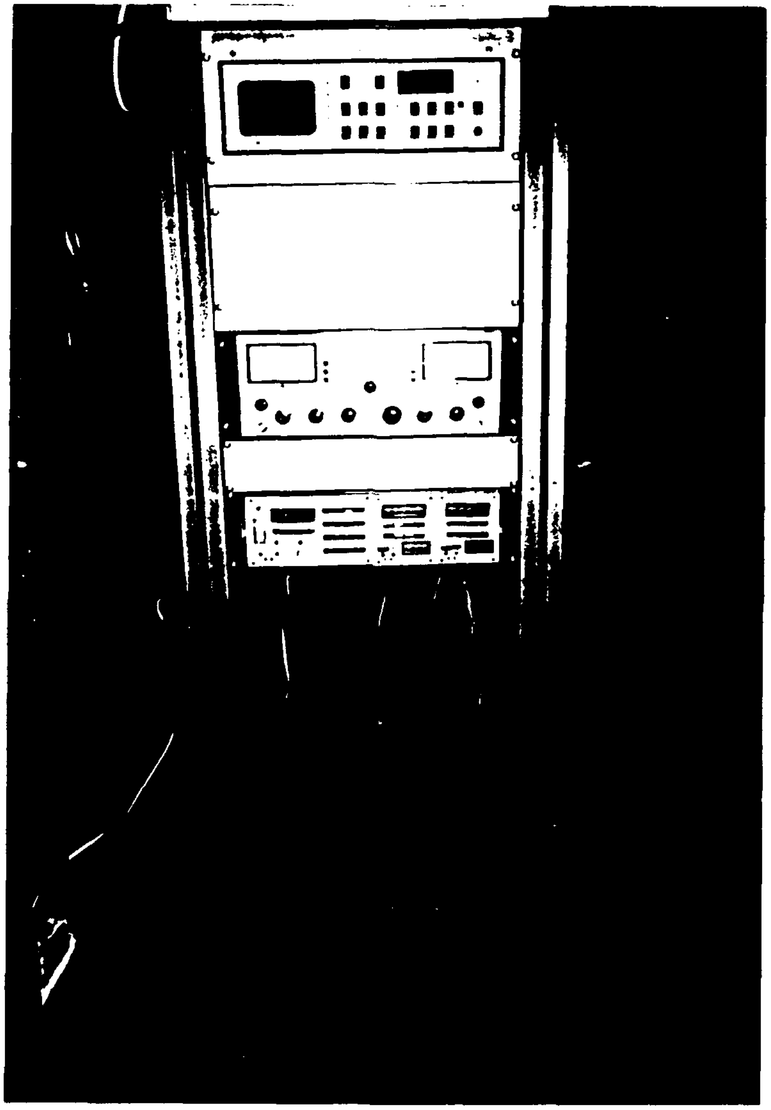
The EXACT function generator should be replaced by one of finer frequency agility and precision, so that all modes and phase shifts within the frequency band of interest can be defined to a finer degree. The replacement must be capable of providing broad band as well as discrete inputs to the exciter.

A calibrated tap hammer should be purchased to augment the function generator and validate data.

B. MISSILE SYSTEM

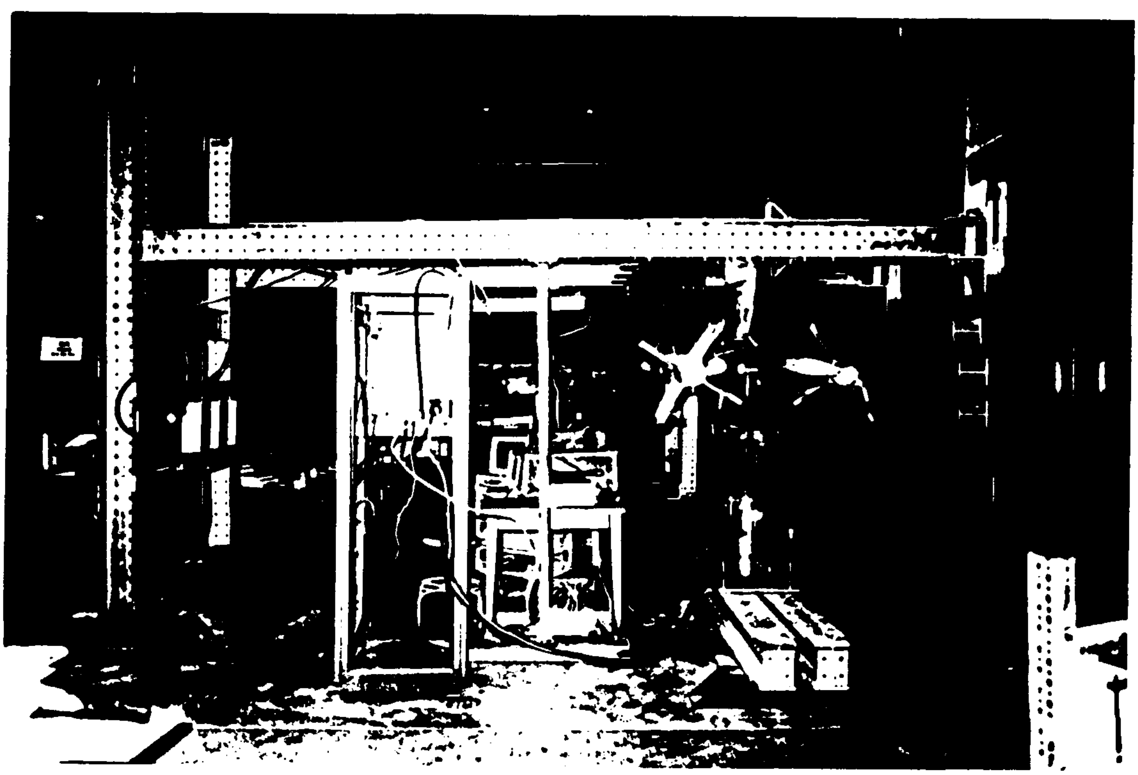
NAVAIR-530, following review of the test results, provide the Naval Air Test Center, Force Warfare Aircraft Test Directorate with the appropriate flight clearances to carry the AIM-9 missile in a single rail/single missile arrangement on wing station 9 and 18, for flutter testing, envelope expansion, and separation tests throughout the limits of the basic air frame. The inflight flutter test should be carried out prior to LBA envelope expansion on station 9. A step down, three altitude profile, at 30000 ft, 20000 ft, and 8000 ft out to Vne, followed by a Mach limit dive will provide total envelope coverage, and can be completed in a single flight evolution. Lateral, longitudinal, and directional, step inputs should be done at 20-25 knot increments (5-10 knot increments at the faster points) throughout the envelope.

APPENDIX A



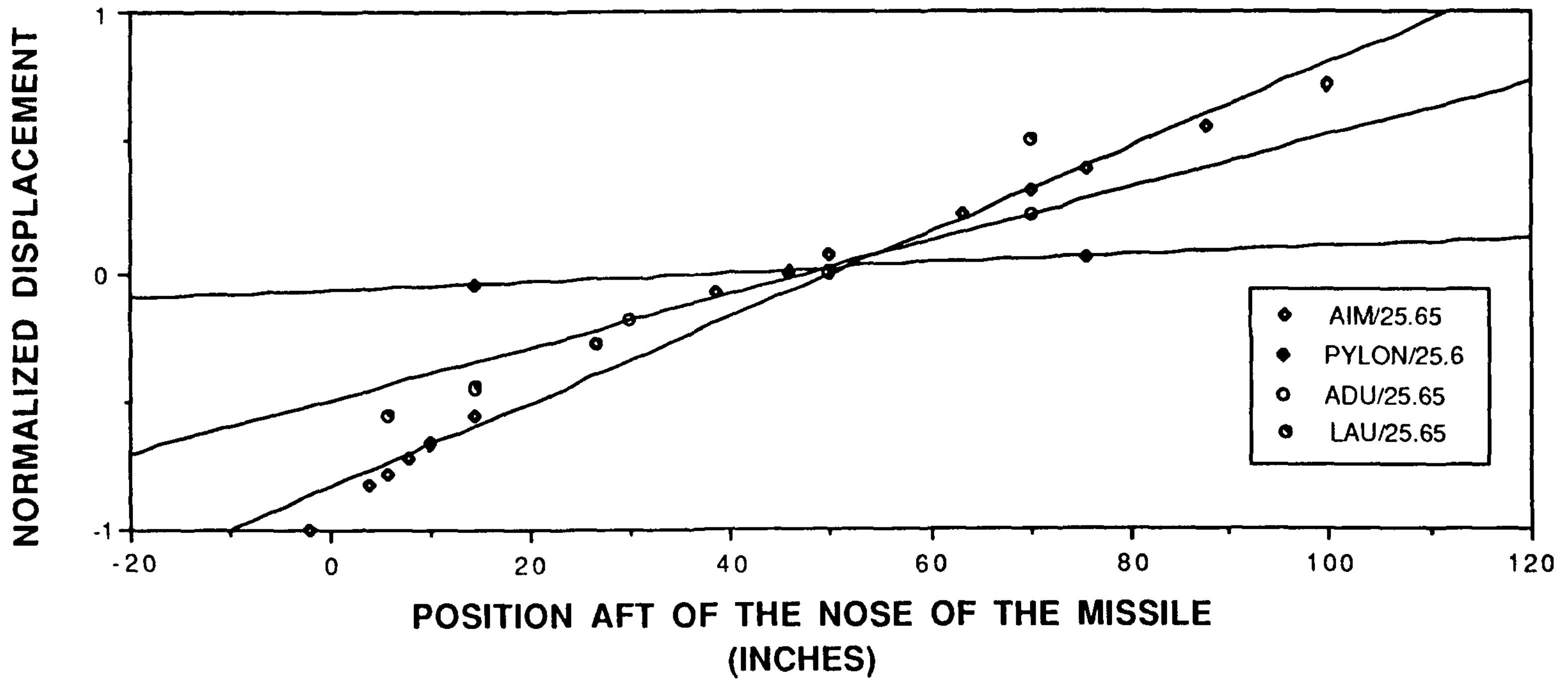
ELECTRONICS RACK

FIGURE 2



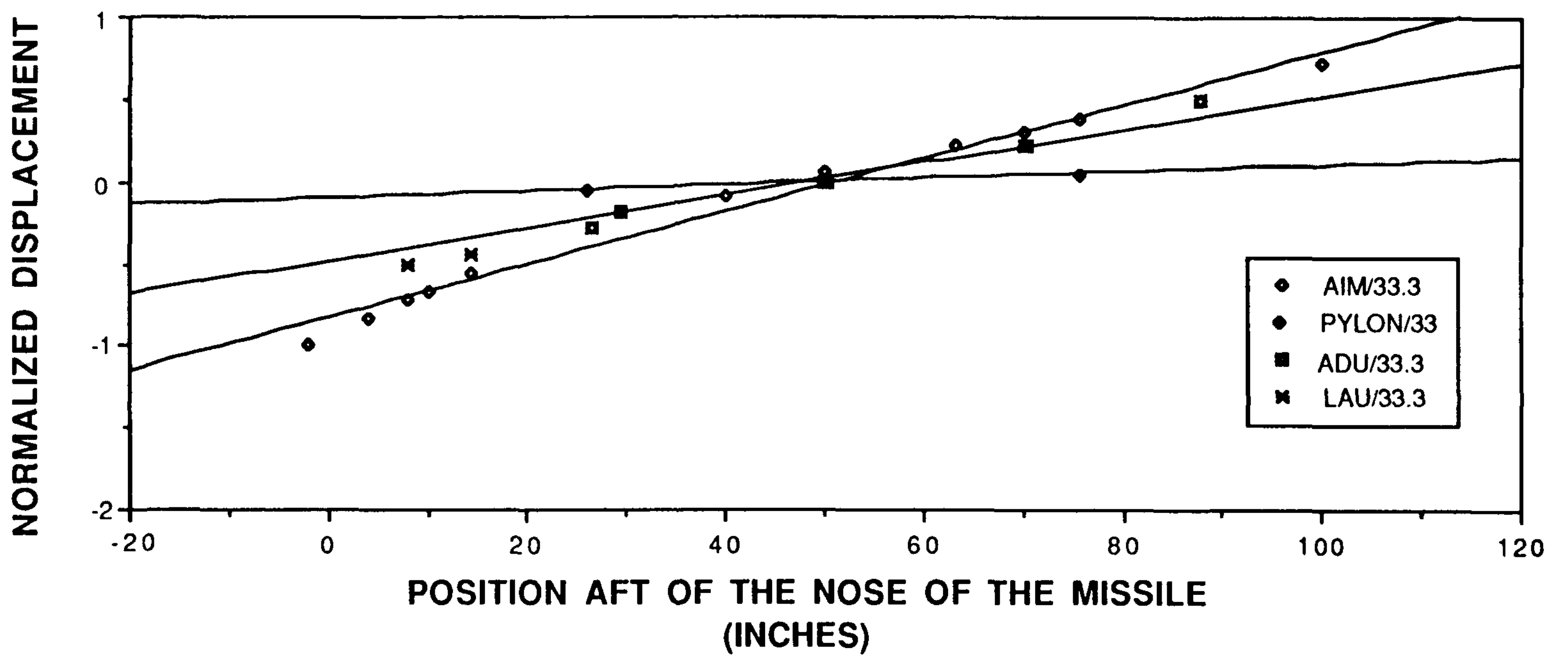
SHAKER MOUNTING BEAMS

FIGURE 4



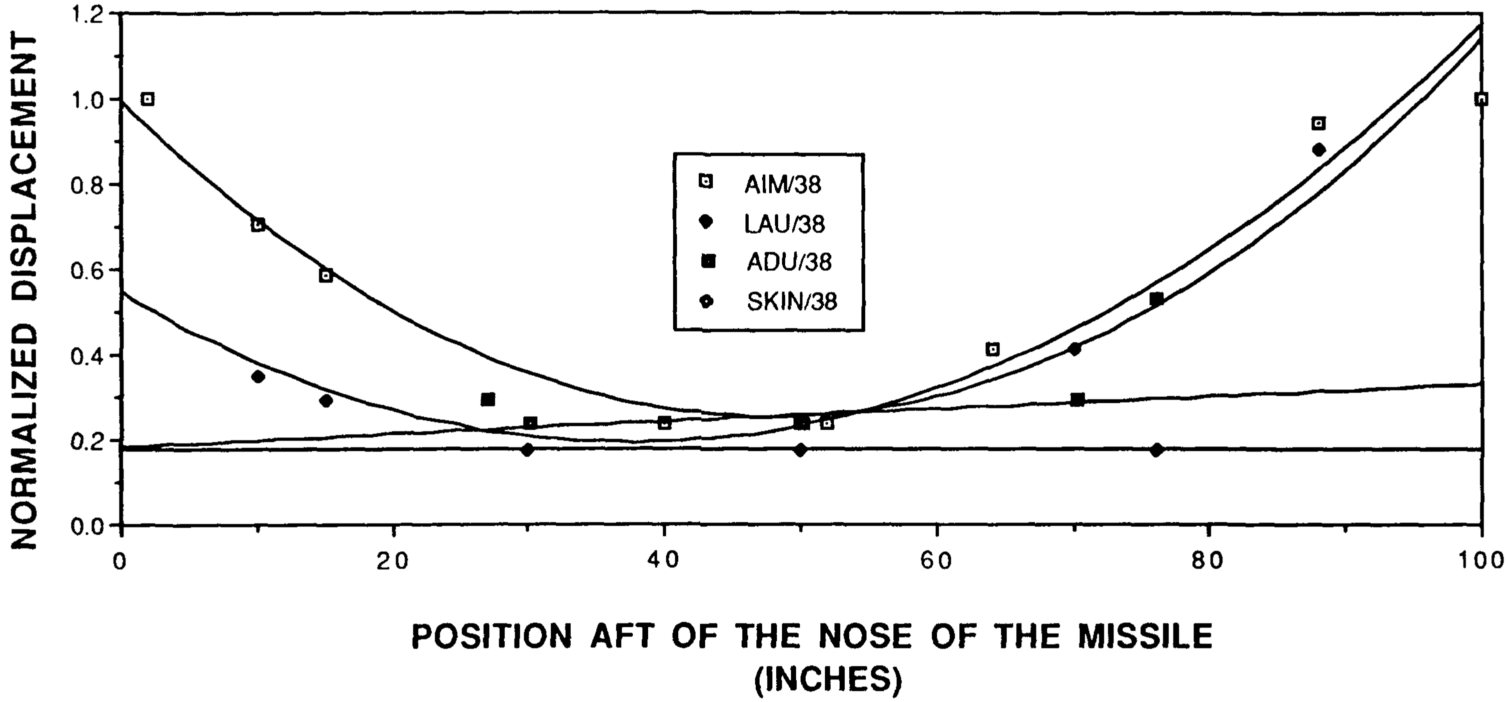
COMPONENT'S POINT DISPLACEMENT VS
POSITION AFT OF THE MISSILE NOSE
(25.6 HERTZ)

FIGURE 9



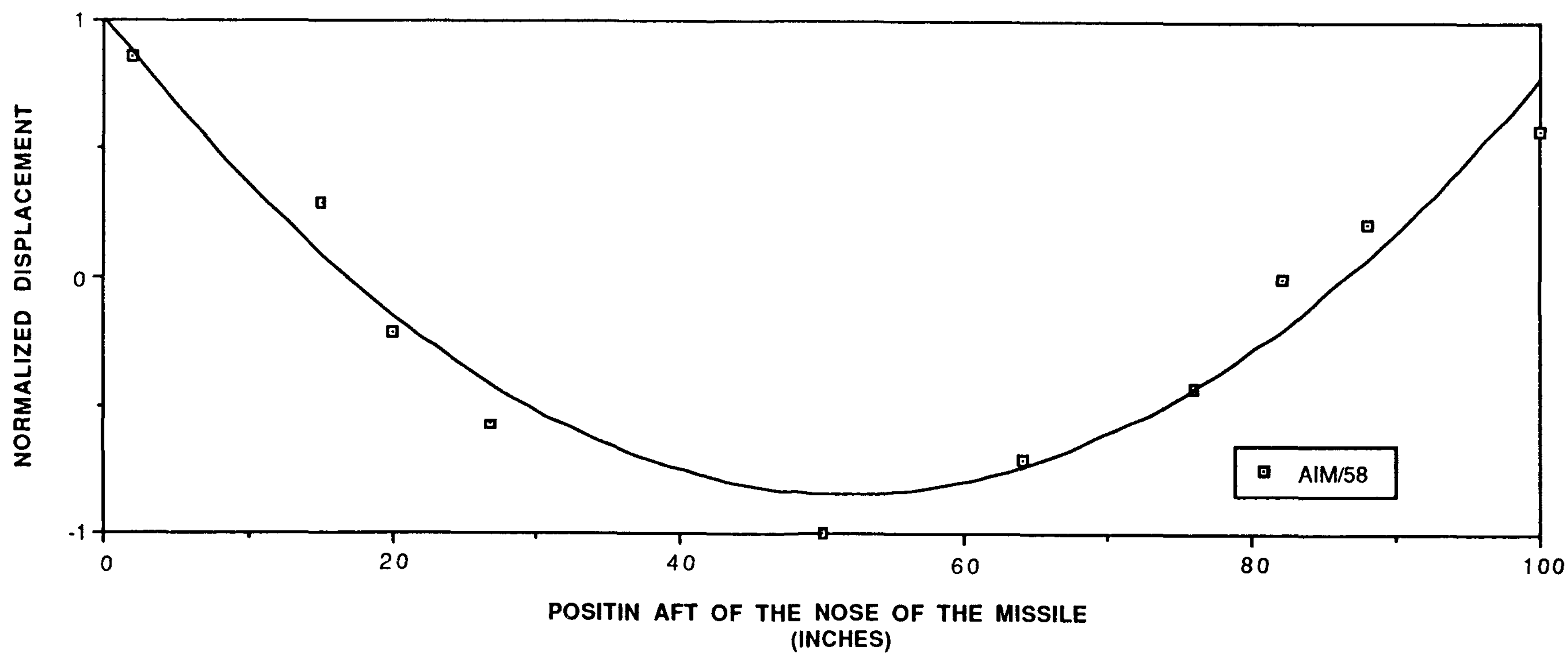
COMPONENT'S POINT DISPLACEMENT VS POSITION AFT OF THE MISSLE NOSE (34 HERTZ)

FIGURE 10



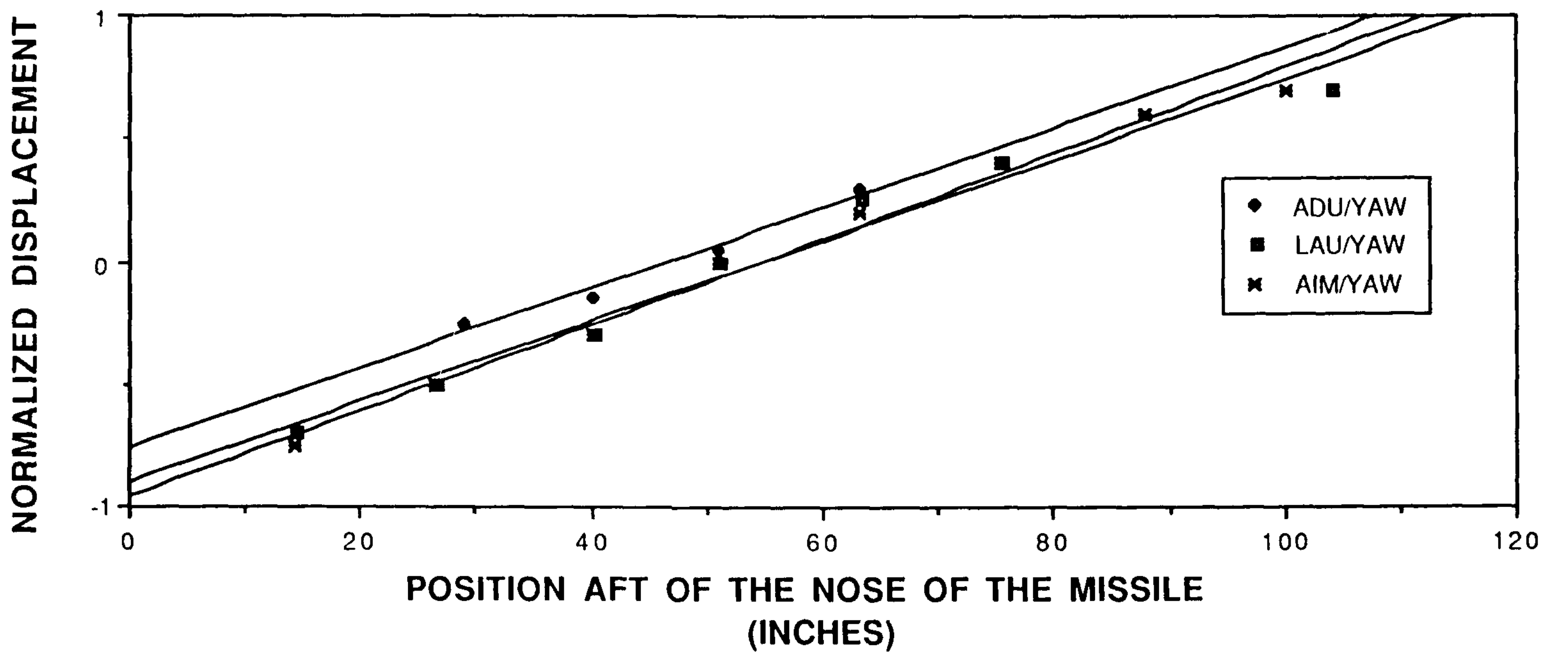
COMPONENT'S POINT DISPLACEMENT VS POSITION AFT OF THE MISSILE NOSE (38 HERTZ)

FIGURE 11



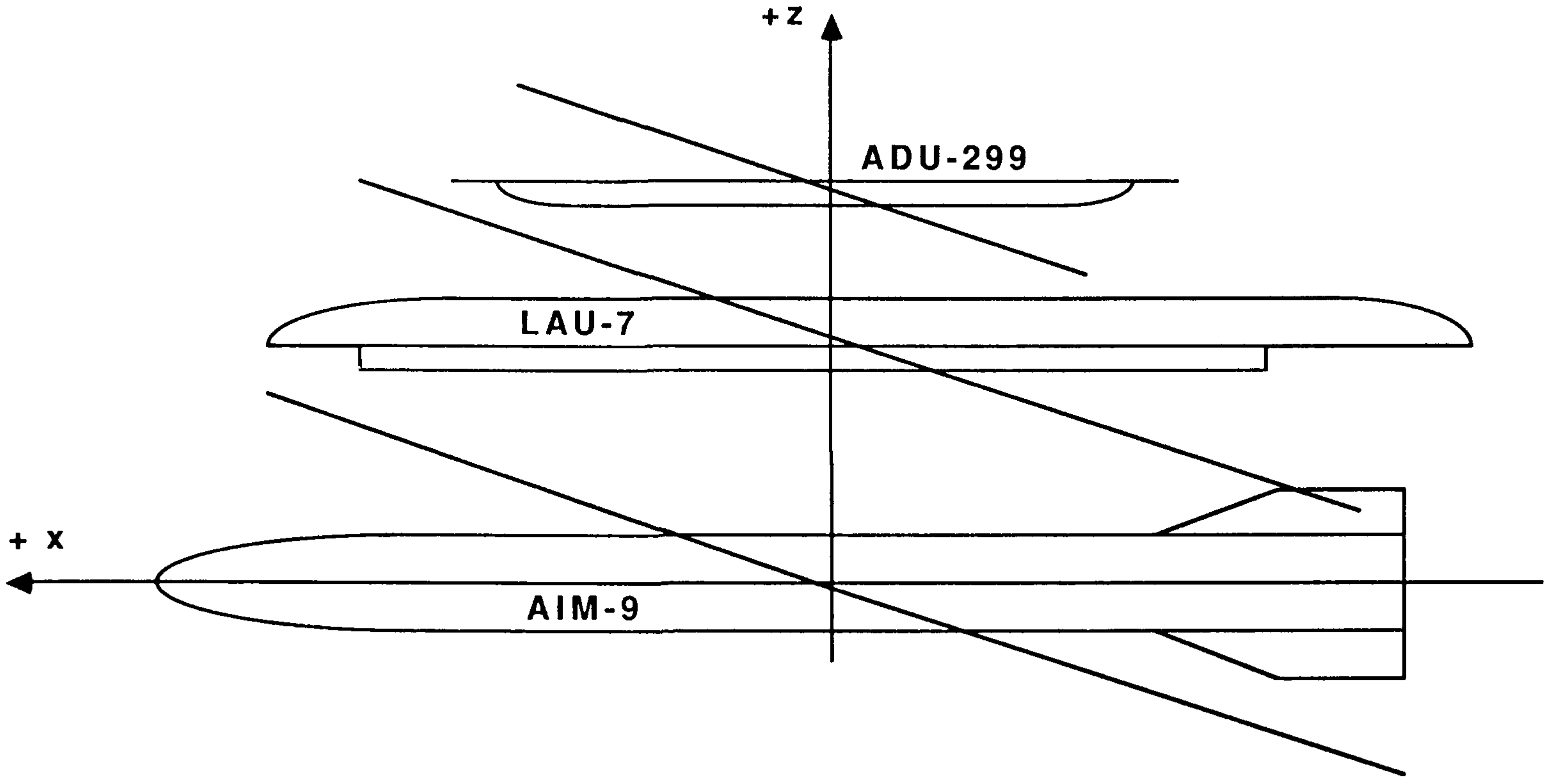
COMPONENT VERTICAL DISPLACEMENT VS LONGITUDINAL POSITION (52.5 HZ)

FIGURE 12

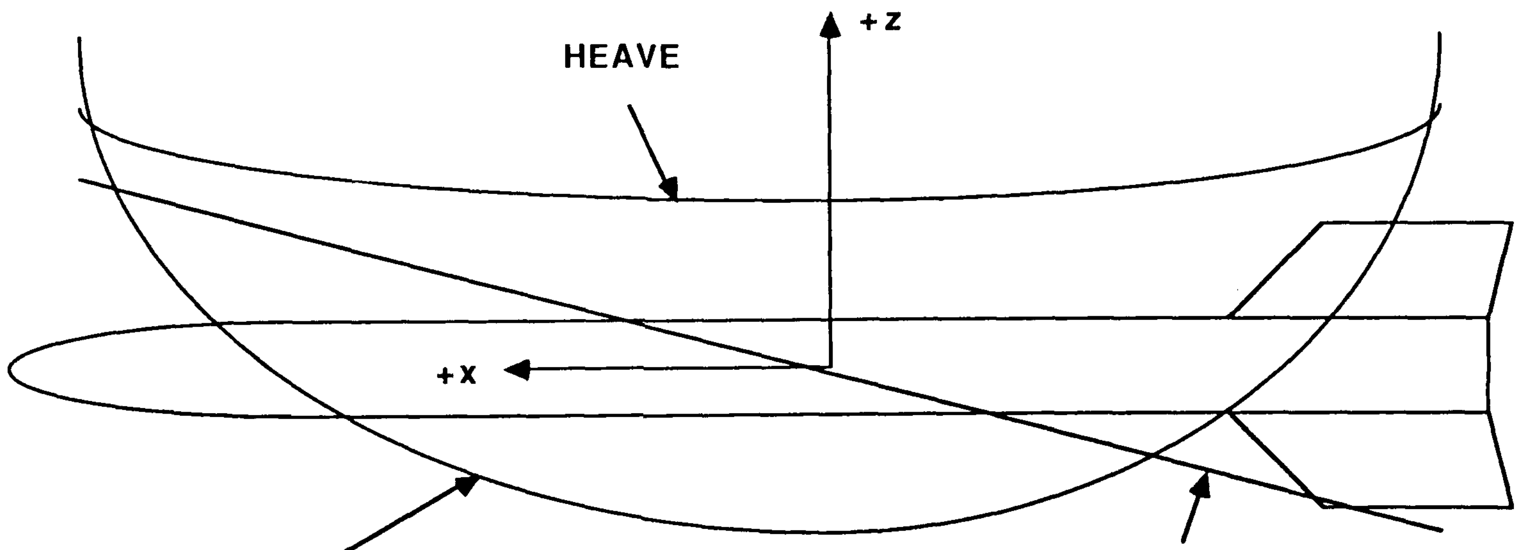


COMPONENT'S POINT LATERAL DISPLACEMENT IN YAW VS LONGITUDINAL POSITION (9.8 HERTZ)

FIGURE 15

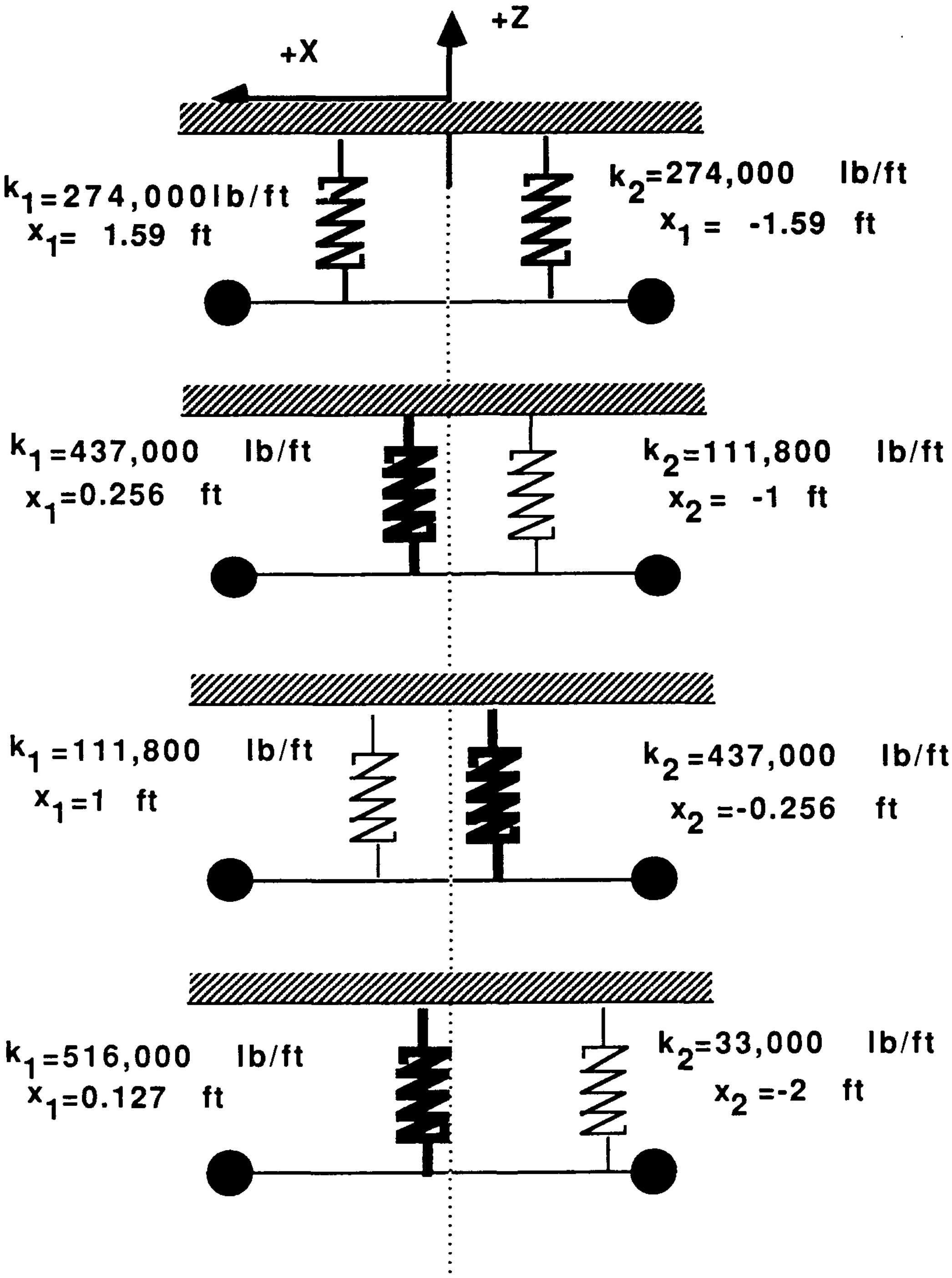


MISSILE SYSTEM COMPONENT BREAKDOWN
PITCH AT 25 HERTZ
FIGURE 16



AIM-9 MISSILE MODE SHAPES

FIGURE 17



SPRING PARAMETERS VARIATIONS
ALL GIVING THE SAME MODAL RESPONSES

FIGURE 19

APPENDIX B

Table I

Accelerometer

Sensitivity Calibrations

PERIOD (SECONDS)	SENSITIVITY CALIBRATION ACCEL 'A' (UNITS)	ACCEL 'B' (UNITS)
0.250	0.232	0.182
0.240	0.232	0.182
0.230	0.232	0.180
0.220	0.232	0.180
0.210	0.232	0.180
0.200	0.232	0.178
0.190	0.232	0.178
0.180	0.232	0.176
0.170	0.232	0.174
0.160	0.232	0.172
0.150	0.232	0.173
0.140	0.232	0.172
0.130	0.232	0.176
0.120	0.232	0.176
0.110	0.232	0.176
0.100	0.232	0.178
0.090	0.232	0.178
0.080	0.232	0.177
0.070	0.232	0.177
0.060	0.232	0.177
0.050	0.232	0.188
0.040	0.232	0.188
0.030	0.232	0.170
0.020	0.232	0.173
0.010	0.232	0.180

Table II

Normalized Component Point

Accelerations in the Vertical at 24.4 Hertz

POSITION AFT FROM NOSE OF MISSILE (INCHES)	24.36 HZ VERTICAL ACCEL ADU-299 (UNITS)	VERTICAL ACCEL LAU-7A (UNITS)	VERTICAL ACCEL AIM-9 (UNITS)
104.000		-1.750	
100.000			-1.000
87.750			-0.850
86.000		-0.650	
75.500		-0.500	-0.700
70.000	-0.250	-0.250	
63.250			-0.500
60.000		-0.100	
58.000			-0.400
56.000			-0.350
51.000			-0.170
50.000	0.000	0.000	
46.000			0.000
42.000			0.000
40.000		0.100	
38.750			0.080
30.000	0.300		0.380
26.500		0.400	0.430
26.000			
24.000			0.550
22.000			0.600
20.000			0.700
18.000			0.730
16.000			0.750
14.250		0.550	0.800
10.000			1.000
6.000		0.950	1.050
2.000			1.100
-2.000			1.250

Table III

Normalized Component Point

Accelerations in the Vertical at 25.6 Hertz

POSITION AFT FROM NOSE OF MISSILE (INCHES)	24.36 HZ		
	VERTICAL ACCEL ADU-299 (UNITS)	VERTICAL ACCEL LAU-7A (UNITS)	VERTICAL ACCEL AIM-9 (UNITS)
104.000		-1.750	
100.000			-1.000
87.750			-0.850
86.000		-0.650	
75.500		-0.500	-0.700
70.000	-0.250	-0.250	
63.250			-0.500
60.000		-0.100	
58.000			-0.400
56.000			-0.350
51.000			-0.170
50.000	0.000	0.000	
46.000			0.000
42.000			0.000
40.000		0.100	
38.750			0.080
30.000	0.300		0.380
26.500		0.400	0.430
26.000			
24.000			0.550
22.000			0.600
20.000			0.700
18.000			0.730
16.000			0.750
14.250		0.550	0.800
10.000			1.000
6.000		0.950	1.050
2.000			1.100
-2.000			1.250

Table IV

Normalized Component Point

Accelerations in the Vertical at 34 Hertz

POSITION AFT FROM NOSE OF MISSILE (INCHES)	33.3 HZ		
	VERTICAL ACCEL ADU-299 (UNITS)	VERTICAL ACCEL LAU-7A (UNITS)	VERTICAL ACCEL AIM-9 (UNITS)
104.000		1.380	
100.000			0.720
87.750		0.500	0.500
86.000			
75.500			0.390
70.000	0.220	0.220	0.310
63.250			0.220
56.000			
51.000			
50.000	0.000	0.000	0.060
40.000			-0.083
29.000	0.190		
26.500		-0.280	-0.280
26.000			
16.000			
14.250		-0.440	-0.560
10.000			-0.670
8.000		-0.500	-0.720
6.000			
4.000			-0.830
-2.000			-1.000

POSITION AFT OF THE MISSILE NOSE (INCHES)	38 HERTZ					
	VERTICAL ACCELERATION AIM-9	VERTICAL ACCELERATION LAU-7	VERTICAL ACCELERATION ADU-299	VERTICAL ACCELERATION BOT PYLON	VERTICAL ACCELERATION TOP PYLON	VERTICAL ACCELERATION GVT SKIN
99.999	1.000					
88.000	0.941	0.882				
76.000	0.529	0.529		0.235	0.235	0.176
70.000		0.412	0.294			
64.000	0.412					
52.000	0.235					
50.000	0.235	0.235	0.235	0.294	0.294	0.176
40.000	0.235					
30.000			0.235	0.176	0.176	0.176
27.000	0.294	0.294				
15.000	0.588	0.294				
10.000	0.706	0.353				
2.000	1.000					

Table V

Normalized Component Point Accelerations in the Vertical at 38 Hertz

Table VI

Normalized Component Point

Accelerations in the Vertical at 52.5 Hertz

POSITION AFT OF THE MISSILE NOSE (INCHES)	52.5 HZ AIM-9 NORMALIZED ACCEL
99.999	0.571
88.000	0.214
82.000	0.000
76.000	-0.429
70.000	
64.000	-0.714
52.000	
50.000	-1.000
40.000	
30.000	
27.000	-0.571
20.000	-0.214
15.000	0.286
10.000	
2.000	0.857

Table VII

Normalized Component Lateral Accelerations

in Sway and Yaw at the Missile System Center of Gravity

VERTICAL POSITION DOWN FROM THE TOP OF THE PYLON (INCHES)	LATERAL ACCELERATIONS IN SWAY AT 7.2 HERTZ (UNITS)	LATERAL ACCELERATIONS IN YAW AT 9.8 HERTZ (UNITS)
0.000	0.000	0.000
-4.000	0.100	0.000
-8.000	0.200	0.000
-12.000	0.300	0.000
-16.000	0.400	0.100
-20.000	0.500	0.100
-24.000	0.650	0.100
-30.000	0.900	0.200

Table VIII

Normalized Component Lateral Accelerations in Yaw

at 9.8 Hertz

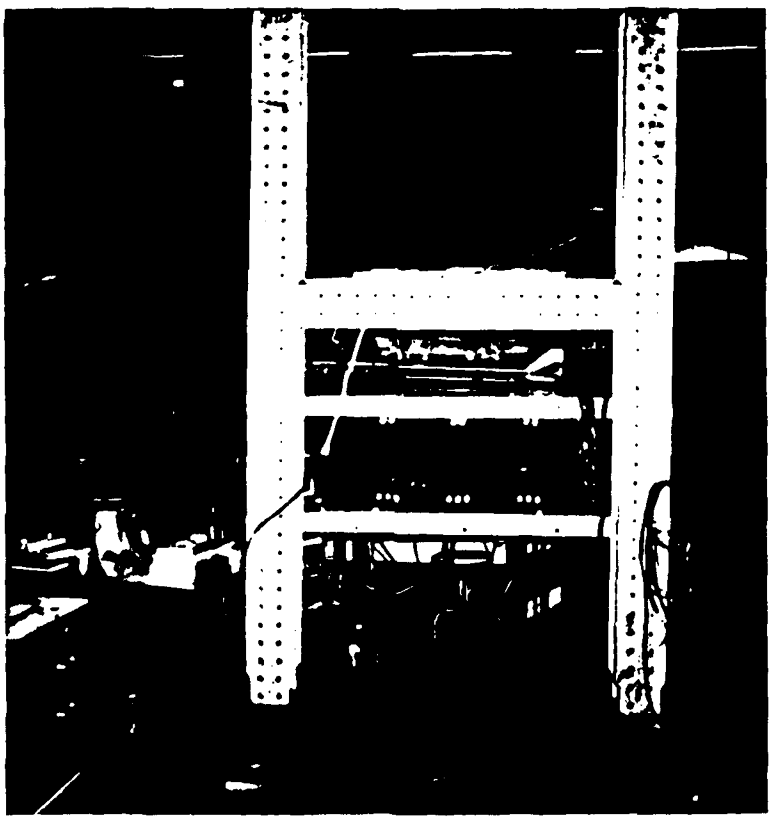
POSITION AFT OF THE NOSE OF THE MISSILE (INCHES)	9.8 HERTZ		
	LATERAL ACCEL ADU-299 (UNITS)	LATERAL ACCEL LAU-7 (UNITS)	LATERAL ACCEL AIM-9 (UNITS)
104.000		0.700	
100.000			0.700
87.750			0.600
86.000			
75.500		0.400	0.400
70.000			
63.250	0.300	0.250	0.200
56.000			
51.000	0.050		
50.000			
40.000	-0.150	-0.300	-0.300
29.000	-0.250		
26.500		-0.500	-0.500
26.000			
14.250		-0.700	-0.750
10.000			
6.000			

APPENDIX C

TEST SYSTEM

TEST STRUCTURE

The test structure is situated on the isolation floor in the basement laboratory of Halligan Hall at the Naval Post Graduate School in Monterey California. A picture of this structure is provided as Figures 1 and 16.



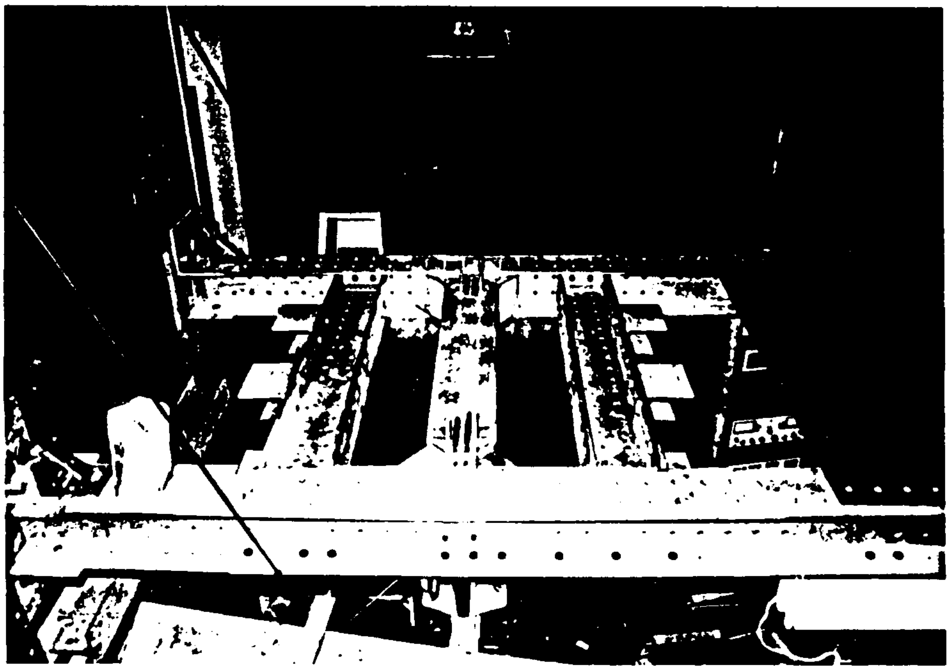
END ON VIEW OF THE GVT

FIGURE 21

It utilizes two of the strong backs anchored in the west side of the floor for its primary support. The GVT was constructed mostly of prefabricated 5, 10, and 15 foot eight-by-eight inch aluminum "I" beams, which were designed to be compatible with the strong backs and isolation floor mounting bolts. Where parts were not available they were fabricated in house, at the machine shop in Bldg 214. The structural portion of the GVT is basically an open rectangle in form, with two parallel 15 foot overhead 8 x 8 inch "I" beams supported 7-1/2 feet above the floor at one end by the strong backs and the other by two vertically mounted 10 foot, 8 x 8 inch "I" beams. These overhead beams are separated by five feet, the distance between the strong backs, and are oriented with the flanges parallel to the floor. Between the overhead beams are three 5 foot 8 x 8 inch "I" beams mounted perpendicular to the overheads, parallel to the floor and separated from each other by approximately 18 inches.These act as stiffener and mounting beams. The two outer beams are oriented with the web parallel to the floor, while the middle beam, which was the main mounting support for the pylon and missile system, was oriented with the flanges parallel to the floor. On this middle beam, extra stiffening of the flanges is accomplished with triangular doubler plates at every intersection, flange to flange, with the overhead beams. A picture of the internal structure is provided below. An upper and lower skin of 3/16 inch 2024 T-6 aluminum was then added to "close the box" and provide rigidity in shear. This

particular aluminum was chosen because of its availability, vice any special properties it may contain. A stiffening cross member was also installed between the two 8 x 8 inch vertical column supports, at the east end, opposite the strong backs. The initial structure was not stiffened in any way over the basic frame and skinned center section. Upon initial excitation of the missile in pitch, a structural resonance began at approximately 13-14 Hz that was not only audible throughout the lab but visible to the naked eye, and caused tools and parts to vibrate off of the structure. Using Rayleigh's principle, the nodes were split twice, almost in half each time. Physical constraints within the space precluded exact bifurcation however the initial fundamental should in theory have quadrupled to 54 Hz. This was in fact nearly the case in that the new resonant frequency of the overhead structure went up to approximately 52.5 Hz. The stiffeners used included 3/8 inch threaded rigid rod and 2-1/4 inch diameter gas pipe. The stiffeners are clearly visible in Figure 17.

The structure was designed to provide minimal motion in the frequency range of interest (up to 50 Hz) to longitudinal test member excitation. There was no stiffening of the internal structure to allow for lateral excitation without motion of the structure.



INTERNAL STRUCTURE OF THE GVT

FIGURE 22

TEST EQUIPMENT

General

The major components of the test equipment were the: Breul and Kjaer Exciter Model 4801; Breul and Kjaer Mulit-Purpose Head Model 4812; Bruel and Kjaer Amplifier Model 2707; EXACT Function Generator; and two PCB Impedance Heads Model 288A11, and their associated amplifiers. Each of these components is briefly discussed below. The general set up is shown in the System V Instructions Manual [Ref. 1], available from any B&K factory representative.

B&K Exciter Model 4801

The Model 4801 exciter was designed to be combined with any one of several Exciter Heads to create a complete exciter assembly capable of generating up to 100 pounds of force. The exciter was chosen for no other reason than its immediate availability. The exciter uses 208 volt, three phase, Delta power transformed to 380 volt, three phase Wye power. It weighs approximately 180 pounds but can be positioned at any angle to provide optimum flexibility and use. With the multi purpose head, the exciter is capable of displacements up to 0.5 inches and has an internal natural frequency of 7200 Hertz and the base has a natural frequency at about 10-14 Hertz. A more detailed description of the exciter is available in the Instructions and Applications booklet, [Ref. 1] for the Type 4801 Exciter available from the Bruel and Kjaer factory representative.

B&K General Purpose Exciter Head Model 4812

The Model 4812 exciter head was designed to provide a low distortion operating band from DC to 10000 Hertz when mated to the Model 4801 Exciter body and the Model 2707 Amplifier. The 'g' loads available for testing vary with the test frequency and run from a low of zero in the DC range to 100 'g' at 150-160 Hertz. More detailed information on the Type 4812 Head is available in the Instructions and Applications booklet for the Type 4812 General Purpose Head, [Ref. 2], from the B&K factory representative.

B&K Power Amplifier Type 2707

The Model 2707 Amplifier was designed to provide proper power and protection to the Exciter, Model 4801. Protective circuits include: signal ground fault; power phase protection; over temperature; displacement; over current; and wave form clipping indications. A more detailed description of the Amplifier unit is available in the Manufactures Instruction Manual for the Power amplifier Type 2707 [Ref. 3], available from the B&K factory representative.

EXACT Function Generator

The EXACT function generator Model 340,utilized for the tests was resurrected from other projects. It is capable of providing various wave forms over a fairly broad range of frequencies. It is not

capable of fine tuning on desired frequencies especially above about 30 Hertz, nor is it capable of amplitude variation of any wave form.

LIST OF TABLES

LIST OF FIGURES

LIST OF REFERENCES

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3. Bruel & Kjaer, *Instructions and Applications, Exciter Body Type 4801*. Orboe Print, Copenhagen Denmark, 1971.

4. Bruel & Kjaer, *Instructions and Applications. General Purpose Head Type 4812*, Orboe Print, Copenhagen Denmark, 1971.

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